Electric field measurements at near-atmospheric pressure by coherent Raman scattering of laser beams

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Abstract. Electric field measurements at near-atmospheric pressure environments based on electric-field induced Raman scattering are applied to repetitively pulsed nanosecond discharges. The results have revealed that the peak electric field near the centre of the gap is almost independent of the applied voltage. Minimum sustainable voltage measurements suggest that, at each discharge pulse, charged particles that remain from the previous pulse serve as discharge seeds and play an important role for generation of uniform glow-like discharges.

1. Introduction
Recently, non-thermal near-atmospheric (or higher) pressure discharges such as those generated in open air have attracted much attention for use in processing that can not be achieved using low-pressure discharges. Application of repetitive high-voltage nanosecond pulses to electrodes is an efficient method of generating such low-temperature high-pressure discharges. However, not many diagnostic reports describe such high-pressure discharges, probably in part because such plasmas are typically small. For that reason, intrusion of even a small solid probe can alter discharge characteristics. Optical methods are therefore preferred as diagnostic techniques for high-pressure discharges. Successful non-intrusive electric field measurements in high-pressure discharges (corona and surface discharges) were reported [1–3] in high-pressure hydrogen gas where Raman scattering by hydrogen molecules was used for field evaluations. The feasibility of electric field measurements in a nitrogen-containing gas has also been achieved and reported recently [4].

In the present study, laser spectroscopy for electric-field induced coherent Raman scattering by hydrogen molecules is used for direct measurement of electric fields in glow-like repetitively pulsed nanosecond discharges in a high-pressure hydrogen gas. The discharges are generated between parallel plate electrodes and the uniformity over the electrode space and reproducibility are fairly good.

In addition to extremely rapid discharge dynamics, including very rapid formation of electric field profiles, as discussed in Ref. 5, it has been found that the peak electric field (near the centre of the...
gap) is almost independent of the peak applied voltage. This might be in part related to prior discharge pulses. The repetition rate dependence of the minimum sustainable peak voltage, which also indicates interaction of successive pulses in a discharge, will also be provided.

2. Experiments

2.1. Electric field measurements with parallel plate electrodes

Figure 1 presents normal digital camera images of discharges, in which we have measured electric fields. Nearly uniform discharges between the metal electrodes seem to be generated by negatively biased nanosecond pulses applied to the cathode (the left electrode in Fig. 1) with pulse duration of about 5 ns and a repetition rate of 10 kHz in pure hydrogen at pressure of 0.3 bar, in all voltage conditions tested in this study. One example of the voltage shape and current flowing into the anode is presented in Fig. 2. The electrodes are stainless steel disks with diameters of 17 mm (cathode) and 14 mm (anode/ground). The discharge gap is 1.15 mm ±0.05 mm. The gas temperature, as estimated by signal strengths of coherent anti-Stokes Raman scattering (436 nm), is 330 K or lower. The electric field is measured by the detection of electric-field induced coherent Raman scattering from hydrogen molecules [1–3,5] by using two pulsed nanosecond laser beams (532 nm and 683 nm) with duration times at full-width at half maximum (FWHM) of 3–5 ns. The reader is referred to ref. 5 for more details on the electric field measurement techniques.

Figure 1. Repetitively pulsed nanosecond discharges generated with parallel plate electrodes in 0.3 atm hydrogen. The gap distance is 1.15 mm; the left side in the picture is the powered electrode (cathode). The peak voltage was about -2.2 kV and the pulse repetition rate was 10 kHz.

Figure 2. Discharge voltage (solid curve) and current (dashed curve) as functions of time during the discharge generation depicted in Fig. 1.

2.2. Repetition rate dependence of minimum sustainable peak voltage with sphere-plate electrodes

In this repetition rate dependence measurement, we used a slightly different electrode geometry. The cathode is a half sphere with a 6-mm radius; the anode is a disk plate. The gap width is set as 1 mm. The minimum peak voltage for sustaining the discharges as a function of the repetition rate and the environmental pressure has been recorded by slowly decreasing the peak voltage while maintaining the repetition rate and the pressure.

3. Results and discussion

Figure 3 presents the measured electric field near the centre of the discharge gap for three voltage conditions. As discussed in Ref. 5, reasonable agreement is apparent between the nominal electric
field (gap voltage/length) and the measured electric field at the very early stage, when significant ionization has not yet taken place. It is noteworthy that extremely good agreement, despite the temporally averaged signals over a few nanoseconds of laser duration, is explainable by the small timing error, i.e. 0.3 ns, which is likely to exist. Although it is not shown in this paper, the spatial distribution is fairly uniform before showing noticeable disagreement near the centre of the gap. The uniform spatial distribution more directly suggests the negligible net charge effects in the space.

Once the voltage is increased to around -1.2 kV, noticeable differences become apparent between the nominal and measured values. As described above, the measured electric field here is more like the averaged one; the first and second signal points showing disagreement might not directly indicate the significant charge effects at that time. For example, for peak voltage of -2.2 kV, the bright emission starts propagating from the anode to cathode sides at around 18.5–19 ns (see Ref. 5), which we believe is synchronized to the ionization front movement. Consequently, the reduction that is apparent around 17.5–18.5 ns is consistent with the phenomenon by which a considerable amount of ionization first takes place with the ionization front propagation starting at around 18.5–19 ns, which finally produces the thin cathode sheath-like positive net charge layer near the cathode [5]. Since there is little time for newly generated ions to reach the cathode to produce secondary electrons, charged particles that remain from the previous pulse should play an important role for the electron production at the cathode. Ions that remain from the previous pulse and stay near the cathode surface can reach to the cathode in a very short time period and produce secondary electrons at the cathode in a single discharge pulse. The emitted electrons, though they may be small in number initially, generate a significantly large number of electrons at the ionization front due to the high gas density and large electric field. Thus the amount of the ionization events should largely depend on the initial charge densities.

Fig. 3 shows that the peak electric field is almost independent of the magnitude of the peak voltage. This indicates that a discharge with higher power input produces a higher-density plasma that shields the electric field more effectively. The stronger shielding is probably caused by more efficient ionizations near the cathode caused by the higher applied voltage and the higher initial charge densities. Since the voltage is repetitively applied, it indicates that, in each discharge pulse, there is a significant amount of plasma charges that remain from the previous pulse in the discharge chamber.

![Figure 3](image-url)

**Figure 3.** Measured electric field near the centre of the gap and nominal electric field as functions of the peak voltage for three different voltage conditions.
Such effects of the previous discharge pulses are also clearly depicted in Fig. 4, showing the minimum sustainable voltages for three repetition rates. In the repetition rate range tested, the higher the repetition rate is, the lower the required minimum voltage becomes. In all conditions presented in Fig. 4, we observed non-filament-like glow-like discharges. Although not shown here, at very low repetition rates such as 10 Hz, a uniform glow-like discharge cannot be maintained stably. That fact probably indicates that numerous electrons and ions remaining from the previous discharge pulse are required as seed charges for the following discharge pulse to obtain uniform glow-like discharges.

Figure 4. Minimum sustainable peak voltage as functions of the environmental pressure for three pulse repetition rates.

4. Summary
Repetitively pulsed nanosecond discharges were studied using electric field measurements based on electric-field induced Raman scattering. Results show an interesting inverse relation between the applied voltage and the electric field near the centre of the gap, possible because the effects of the previous discharge pulses are provided with supporting results of sustainable voltage as a function of the repetition rate. This kind of repetitively pulsed nanosecond discharges probably requires the initial seeded charges from the previous discharge pulses for such uniform glow-like discharge generation. With the low repetition rate, with intervals too long to retain a considerable amount of seeded charges, discharges likely turn to localized filament-like discharges.

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