Antenna measurement of electric field and higher harmonics in atmospheric plasma jets interacting with different targets

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Cold atmospheric pressure plasma jets (APPJs) are used in many applications (*e. g.*, material treatment, gas conversion, plasma activation of water, and plasma medicine) with widely differing setups: ignited into an open space or against a target, which can be dielectric or metal, grounded or floating. Therefore, understanding how the target properties affect the fundamental plasma parameters is crucial for optimizing the jet application. The electric field is one of the most essential discharge parameters because its magnitude determines the production and energy of the charged particles, hence the plasma chemistry. However, the measurements of APPJ electric fields are scarce due to the hard requirements on either the equipment (high-power picosecond lasers are needed for the electric field-induced second harmonic generation [1] and coherent anti-Stokes Raman scattering measurements [2]) or on the plasma gas chemistry (methods based on optical emission spectroscopy [3, 4]). Measurements by electro-optic sensors based on the Pockels effect [5], although not species-specific or overly experimentally demanding, require discharge to be in contact with the sensor, thus affecting the plasma parameters.

We present an alternative approach to measuring the APPJ electric field using antennas. This relatively simple and non-expensive method provides a semi-quantitative value of a discharge macroscopic electric field. Measurements of spatial or temporal distribution are not possible. The antennas can also non-intrusively monitor discharge nonlinearity (generation of higher harmonics, subharmonics, and ultraharmonics), presenting an alternative to current probes for setups with inaccessible electrodes.

The RF ($f = 13.56$ MHz) plasma slit jet (PSJ) and plasma capillary jet (PCJ) were ignited against several different targets (Fig. 1a): floating dielectrics of different permittivities, dielectrics with a ground beneath, a water surface, and a grounded aluminum plate. Both the discharges use Ar as working gas. In the PSJ, Ar could be mixed with different additives (O_2, N_2, and H_2O aerosol). The plasma jets' nonlinearity and electric field were measured by commercial biconical antenna BicoLOG 20300 (350 mm diameter). All the measurements were carried out in the reactive near-field region. In this region, the radiated electric field can be modified by coupling of the antenna and discharge or distorted by adjacent conductive objects absorbing and re-emitting the radiation. The affected cases were identified by comparing the antenna frequency spectra against the frequency spectra of discharge current measured by a current probe at the grounded electrode. The antenna records effective voltage induced at the connector by a global mix of external electric fields. During the recalculation, we approximated the different sources by the electric field of the plasma sheath, which is expected to be the highest contributor.

All the measured frequency spectra shared one feature, a dominant fundamental frequency peak (Fig. 1b). The relative intensities of other peaks differed with the plasma jet. The PSJ frequency spectrum contained relatively intense odd harmonics and significantly weaker even harmonics. This alternation of relative intensities was more pronounced after the admixing of molecular gas (Ar/N_2 PSJ spectra in Fig. 1b). The intensity of even harmonics was presumably connected with the volume ionization. Molecular gas admixing led to its decrease, which was reflected in the higher nonlinearity of the discharge. The appearance of weaker even harmonics is linked to the opposing action of parallel sheaths that form inside the slit. The intensity of even harmonics increases as the symmetry of the opposing sheaths decreases. In the Ar/N_2, the abundant long-lived nitrogen metastables were more likely to diffuse onto the slit surface, knocking out an electron from it, thus distributing the sheaths symmetry. The PCJ nonlinearity was lower compared to the PSJ ignited against the same target (Fig. 1b). Moreover, as no opposing sheaths formed on the inner discharge capillary walls, the even and odd harmonics had

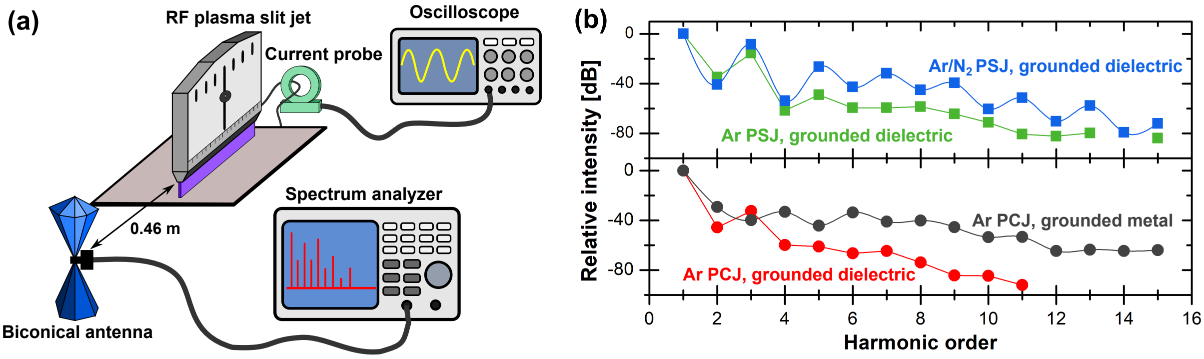

Fig. 1: (a) Schematic drawing of the experimental setups used for antenna measurements. The PSJ is used to demonstrate the position of a plasma jet. (b) Relative intensities of higher harmonics measured by the biconical antenna for PSJ and PCJ ignited against different targets. The PSJ settings were 67 slm of Ar, 1.5 slm of N_2, and 500 W applied power. The corresponding PCJ settings were 5 slm Ar and 50 W. In all the measurements, the distance between the jet outlets and the target surface was 10 mm.

similar relative intensities. The higher relative intensity of 3rd harmonic (Fig. 1b) was unrelated to the processes occurring inside the discharge tube, as it was enhanced only in the presence of a grounded dielectric target.

The target influence on the PSJ nonlinearity differed with the gas chemistry. Using a grounded dielectric target as an example, the relative intensities of odd harmonics in the Ar PSJ spectrum decreased compared to the open space configuration when the plasma impinged on the target surface, presumably due to the enhanced volumetric ionization. On the other hand, the frequency spectra of the Ar/N_2 PSJ were identical for both the open space and the grounded target configurations, as the addition of molecular gas limited the probability of ionizing collisions. In the PCJ, the target influence was connected to how the plasma filament interacted with its surface. The PCJ nonlinearity was low when the filaments formed a broad base on the target surface (grounded dielectric targets of different permittivities). Conversely, when PCJ impinged on conductive targets, the filament attached itself to the surface in a small circular spot. This anode attachment caused a drastic increase in the relative intensities of higher harmonics, starting with the fourth. Furthermore, in contact with the metal, many peaks with random frequencies caused by random sparks appeared in the spectra.

Though the obtained values of the electric field were only semi-quantitative (10–200 kV/cm, depending on the jet and the configuration), the antennas exhibited high sensitivity to the changes. Out of the studied gas feeds, the strongest electric field was generated in pure Ar discharge. Admixing of oxygen or nitrogen gas halved the measured strength. As for the target influence, only the conductivity and grounding had any notable effect. The dielectric permittivity and the ground configuration (plate, mesh) had negligible impact on the final value. The electric field of the PSJ impinging on the grounded target was, on average, 2× higher than in the floating target configuration and 3–4× higher than in the open space configuration. The PCJ results demonstrated the effect of target conductivity. The highest electric field was induced when PCJ impinged on the grounded aluminum target, followed by the water surface, and the lowest strength was obtained for the grounded dielectric targets (about 3× lower than for the metal target).

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