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# On the Bullet-Streamer Dualism

Stephan Reuter, Ansgar Schmidt-Bleker, Sylvain Iseni, Jörn Winter, and Klaus-Dieter Weltmann

**Abstract**—Formerly so-called bullet jets have been in the focus of atmospheric pressure plasma jet research of the past years. In this paper, two perspectives of the dynamic phenomenon are presented. Averaged, the dynamics appears as a bright spot—the so-called bullet—traveling from the plasma jet nozzle. In single shot it is revealed that the discharge mode in fact is a streamer-type discharge leaving the jet nozzle into the ambient.

**Index Terms**—Atmospheric-pressure plasmas, fluorescence, plasma diagnostics.

## I. INTRODUCTION

**S**O-CALLED plasma bullet jets exhibit bright dynamic features appearing as bright spots traveling from the plasma jet nozzle into the ambient surrounding [1]. These cold plasma jets are typically in the millimeter scale. A typical field of application of these jets is plasma medicine. Several works have already shown that the bullet is connected to the nozzle by a tail like structure [2] and can be snake like [3]. Usually, these jets are operated in pulsed or kHz mode [4], [5]. Recently, these features have been observed also in a plasma jet operated at  $\sim 1$  MHz [6].

In this paper, a plasma jet, the so-called kinpen [7], developed by the INP Greifswald is investigated. It is operated within a turbulent flow regime at three standard liter per minute of argon with no admixture in open air. For the single-shot images, over only one excitation period, a CCD camera (Imager Pro X, LaVision GmbH, Germany) combined with an external gated image intensifier is used with a gate width of 5 ns. It has a high sensitivity and can thus detect single shot images of the discharges effluent. For the bullet images, phase resolved optical emission imaging is used [ibid.]. For these measurements, an intensified CCD-camera (Picostar, LaVision GmbH, Germany) is triggered repetitively at the same point of phase in the duty cycle of the excitation frequency of the plasma. An averaged image ( $> 200\,000$  excitation period) is recorded at a fixed gate width of 1 ns acquired at each excitation period. Subsequently, the trigger point is shifted toward a later point in the duty cycle phase and the process is

repeated. The result is a time-averaged movie of the emission pattern during a whole duty cycle (or longer). If the plasma jet exhibits the bullet characteristics, these bullets appear as a moving emission packet in the effluent with speeds of up to several 10.000 m/s. It is now agreed that the bullets rather are streamers and ionization fronts. In the following, it is shown that the observation of this bullet behavior depends on the measurement technique used.

From this paper, it is clarified that the appearance of the plasma jet is due to the way it is measured. At short exposure times of a few nanoseconds, the ionization front becomes visible [see Fig. 1(a) and (b)]. Acquisition of only one excitation period exhibits the streamer-like nature of the discharge [Fig. 1(a)] with a tail connecting the streamer head to the nozzle, as has been observed for other plasma sources [8]. The head has a much stronger intensity. The streamer path follows a nonregular pattern, which can be attributed to the path of purest argon, determined by impurity diffusion, as previous investigations have shown [9]. Averaging over many periods of excitation, but fixing the exposure gate to one phase point exhibits a feature, which had been described as a plasma bullet. Here, the varying streamer path results in a weaker emission connected to the nozzle [Fig. 1(b)].

Taking longer exposure gates over the whole period will reveal the complete streamer pathway [Fig. 1(c)].

Averaging over many periods will show the plasma jet as seen by the naked eye in a flame-like appearance [Fig. 1(d)].

From the investigations, it can be seen that the bullet pattern observed by PROES measurements is a result from the averaging procedure. The streamer head [in Fig. 1(a)] results in the bullet feature observed in Fig. 1(b) when averaged over a large number of periods (due to technical reasons, the phase point is not exactly the same for both measurements).

On the timescale of the bullet propagation, the vortices in the flow field appear stationary and the discharge follows the winding argon channel as revealed by the single shot measurements. Averaging over many periods at the same phase position yields a smoothed emission pattern.

Concluding, it can be remarked that the investigated plasma jet can appear either as a bullet jet, if imaging is averaged over a larger number of periods or as a streamer discharge if observed in single shot mode. This is the bullet-streamer dualism in the atmospheric pressure plasma jet. For modeling and for diagnostics as well as for the application field, these different appearances have to be known and taken into account.

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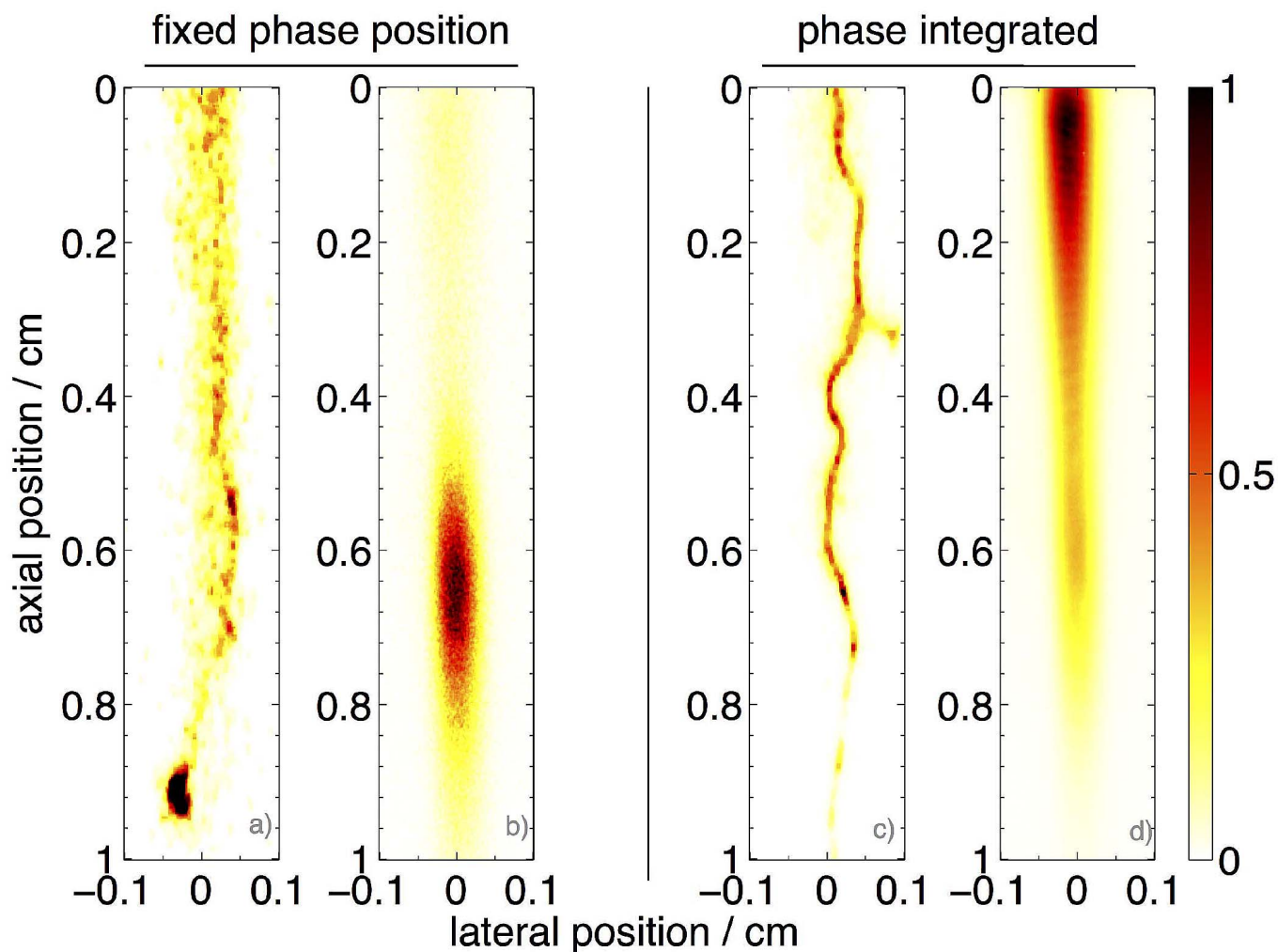


Fig. 1. Contrasted perspectives of the effluent of an atmospheric pressure argon plasma jet. The intensity scale is given in relative units. The lateral scales range from  $-0.1$  to  $0.1$  cm for each data set. (a) and (c) taken over one excitation period with a gate width of (a) 5 ns and (c) over the whole period. (b) and (d) taken over many excitation periods ( $>200\,000$ ) with a gate width of (b) 1 ns and (d) over a whole period. While (a) and (c) show the wavelength integrated emission of the jet, an optical filter imaging the argon emission at 706.7 nm was used in (b) and (d) in order to cut the emission from long-living excited species.

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