Small-Size Ionization Source Based on a Piezoelectric Micro Plasma

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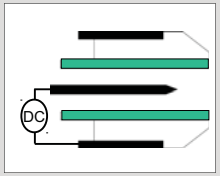
Introduction

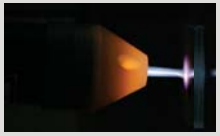
Ionization of neutral atoms or molecules is an important prerequisite for mass spectroscopy as well as for many other scientific applications. However, most of the traditional ionization sources have severe drawbacks, e.g. they may be operated at reduced pressure only, require hazardous high voltages, and add contaminations to the samples. We investigate technology and physics of a novel piezo-electric driven plasma source and compare it to corona-type and classical dielectric barrier discharges [1,3,4,6].

Classical Ionization Sources

Corona-type Discharges



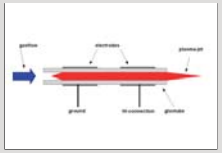
- needle metall electrode
- inhomogeneous electric field
- positive and negative corona
- dc and ac operation possible



Pros:
- easy
- cheap

Cons:
- needle degeneration
- high voltage required
- contamination

Dielectric Barrier-type Discharges



- ac operation required
- at 1 bar gas flow rates 1…10 l/min
- power consumption typ. some W
- operating frequency 1… 100 kHz
- commercially used for ozone prod.

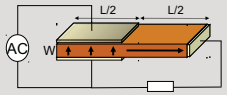
Pros:
- electrodeless
- no contamination

Cons:
- high voltage required
- sophisticated power supply

Novel Ionization Source Based on the Piezoelectric Transformer

input V_i:
- low ac voltage
- primary part
- inverse effect

output V_o:
- high ac voltage
- secondary part
- direct effect

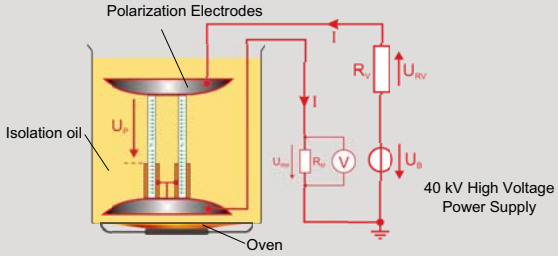


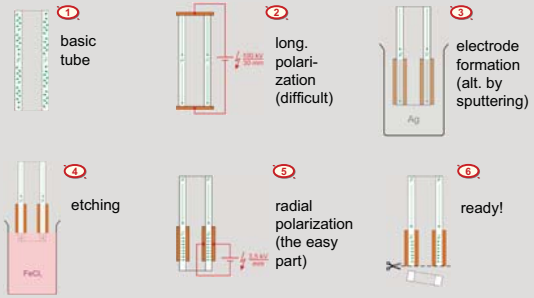
Output voltage high enough for gas breakdown!

$V_o/V_i \propto L/W$

Piezo Polarization Process

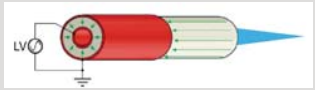
Experimental Setup and Processing:





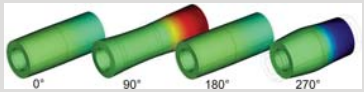
Final Product

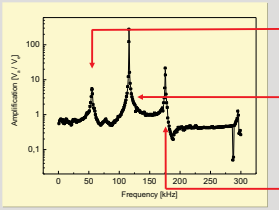
Schematic of piezo plasmajet
l=25mm; d_a=5mm; d_i=3.2mm



Piezo Oscillation Modes and Voltage Amplification

very complex vibration modes possible: FEM simulation of piezo transformer operation modes (ideal case)



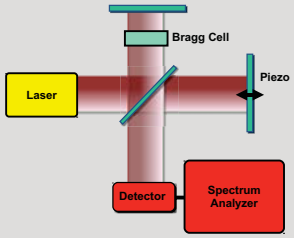


mode λ/2
freq f_0

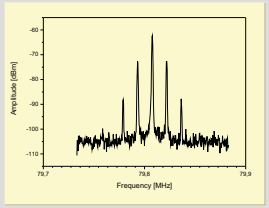
mode λ
freq $f_1 = 2f_0$

mode 3/2 λ
freq $f_2 = 3f_0$

Characterization of Electro-Mechanical Properties by Vibrometry



Laser Vibrometer (Michelson Type)



$$I(t) = I_0 \sum_{n=-\infty}^{+\infty} J_n(\eta)\cos(\omega_B t + n\omega_Y t)$$

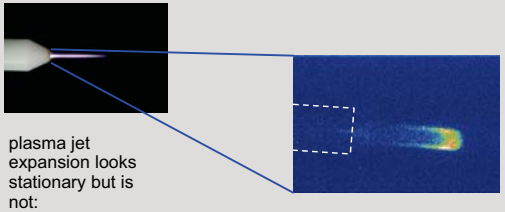
$\eta = 4\pi s_0/\lambda$

s_0: vibration amplitude

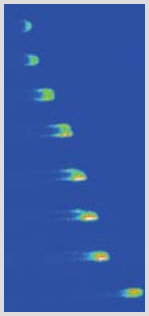
Piezo motion control (measured without plasma):
- typical some nm vibration amplitude
- for a 30 mm piezo driver
- and some volts excitation voltage

Small-Size Ionization Source Based on a Piezoelectric Micro Plasma (Cont'd)

Phenomenon Plasma Bullets



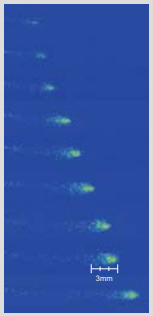
plasma jet expansion looks stationary but is not:
small-size plasma bullets are emitted from the nozzle and move with high velocities!



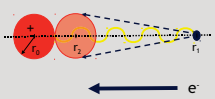
plasma bullet evolution
- exposure time: 50ns
- delay: 100 ns
- bullet velocity 10-25 km/s

left image sequence:
classical DBD (with quartz tube) 13 kHz; 4 kVpp (half-mode) 6 slm He

right image sequence:
piezo DBD, 116 kHz, 75 Vpp, 5 slm He



Plasma Bullet Model



model from Dawson and Winn [7]

- luminous "streamer head" is essentially a positive space charge cloud
- generates **photoionization** at some distance in front of head
- accelerated electron causes avalanche towards head
- positive head is neutralized but electrons leave a new positive region

=> HEAD MOVES!

model requires $N_i > 3 \times 10^9$

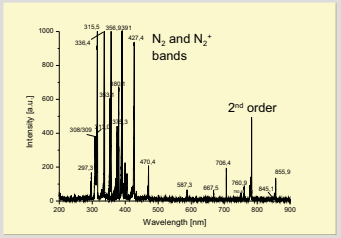
- here: $N_i = 10^{11}$
- conservative estimation: r_1 in mm range

=> bullet is an ionization wave similar to a streamer!

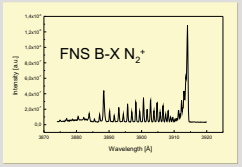
Next step: modified fluid model

$$\frac{\partial n_e}{\partial t} + \nabla(\vec{v}_e n_e) = S_{ion} + S_{photo}$$
$$\frac{\partial n_i}{\partial t} + \nabla(\vec{v}_i n_i) = S_{ion} + S_{photo}$$
$$\Delta\Phi = -\frac{e}{\varepsilon_0}(n_i - n_e)$$

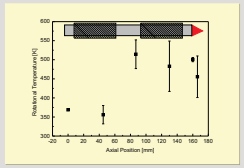
Diagnostics: Optical Spectrum from free Jet Expansion in Air



optical emission spectrum from the DBD jet: mostly nitrogen spectral features

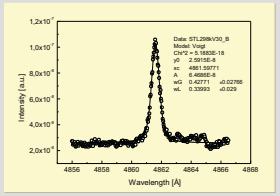


nitrogen ion ro-vibrational band spectrum enables determination of rotational temperature via Boltzmann plot [4]



temperature distribution within the DBD-type non-thermal atmospheric pressure plasma jet

Diagnostics: Electronic Density Estimation from Stark Spectroscopy



measurement of H_b line with 1 m monochromator, 2400 lines/mm

(details published in [4])

- line broadening mechanisms:
  - Van der Waals
  - Stark
  - Doppler
- electron density $5 \times 10^{12} \ldots 5 \times 10^{13}$ cm^{-3}
- evaluation method from: Laux et. al. *Plasma Sources Sci. Technol.* 12, 125 (2003)

Technical Realizations and Improvements

jet in Argon using additional needle electrode

operation in closed Helium atmosphere (easy) between plate piezos

operation in free air between plate piezos (15 V primary voltage only!)

Conclusions

- an efficient small-size non-thermal ionization source has been built based on the **piezo-electric plasma generation principle**
- produces jet plasma consisting of triggerable plasma bullets
- operates at atmospheric pressure
- can be realized with or without electrodes
- requires only low (primary) voltages
- high voltage amplification
- electrically safe e.g., no shock when touching the ceramics
  -> benefitial to medical applications
- design flexibility
  -> different geometries, tubes, plates, coupled sources ("piezo stacks" etc.) possible

References

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[3] International Patent WO2007006298
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[5] B. L. Sands, B. N. Ganguly, K. Tachibana, *IEEE Trans. Plasma Sci.* **36**, 956 (2008)
[6] H. Kim, A. Brockhaus and J. Engemann, *Appl. Phys. Lett.* **95**, 211501 (2009)
[7] G.A. Dawson and W.P. Winn, *Z. Phys.* **183**, 139 (1965)