Masaryk University Brno
Department of Physical Electronics

Atmospheric Pressure Plasmas – Basics and Applications

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Atmospheric pressure plasmas

Lecture I: Introduction, overview on sources and selected applications
- Incidences, Electrical breakdown
- Types and classification of atmospheric pressure plasmas
- Selected applications

Lecture II: Diagnostics of non-thermal atmospheric pressure plasmas
- Electrical characterization
- Optical emission spectroscopy, fast optical/spectroscopic methods
- Surface charge measurements

Lecture III: Environmental aspects of plasma science
- Plasma chemistry
- Depollution of gases
- Treatment of liquids

Lecture IV: Plasma life-science applications
- Biological decontamination
- Plasma medicine

Atmospheric pressure plasmas I

Introduction, overview and selected applications

1. Introduction
   - Incidences and relevance
2. Basics
   - Electrical breakdown
   - Thermal and non-thermal plasmas
   - Scaling laws and miniaturisation
   - Classification
3. Arc discharges and plasma torches
4. Barrier discharges
5. Corona discharges
6. Plasma jets
7. Microplasmas
8. Summary

INP Greifswald

Atmospheric plasmas

1. Introduction: From lightnings to microplasmas

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Pressure range

$\log_{10}$ pressure

High Pressure

1.013 10^5 Pa – 1013.25 mbar → Atmospheric Pres. (AP) **"Atmospheric Plasmas"**

Low Vacuum

3 10^3 Pa – 30 mbar

Medium Vacuum

10^{-1} Pa – 10^{-3} mbar

High Vacuum

10^{-7} Pa – 10^{-9} mbar

Extremely High Vacuum

10^{-10} Pa – 10^{-12} mbar

→ Plasmas in standard air
→ Plasmas in open atmosphere
→ Plasmas at elevated press.

Lightnings

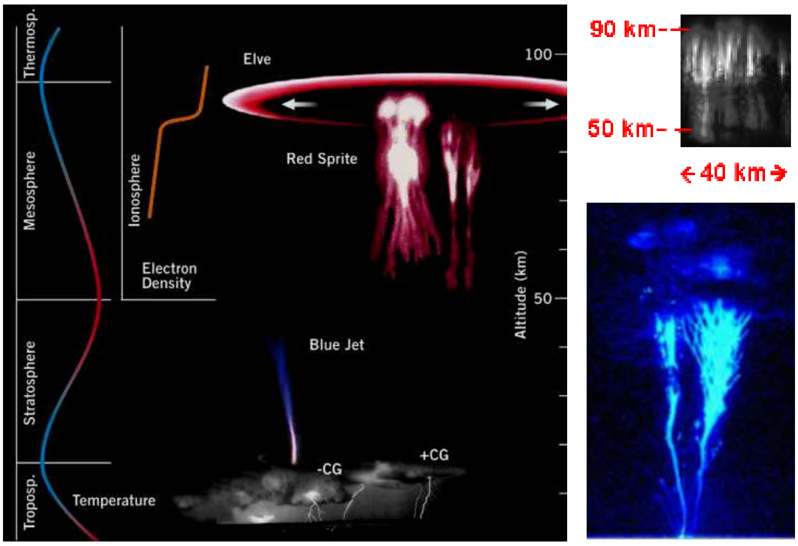
- speed up to of 60,000 m/s
- temperature up to 30,000 °C
- current 5 – 20 kA (up to 200 kA)
- electric field: 3-4 kV/cm
- total power: sev. hundred MW

1) cloud-to-ground lightning CG
2) intracloud lightning CC
3) cloud-to-air lightning CA

M.A. Uman "All about lightning" Dover Publications, New York

„Megalightnings“ (upper atmosphere)

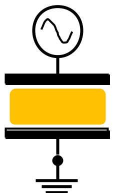
▪ transient luminous events (TLE)



T. Neubert, Science, Vol 300, 2 (2003) http://www.eurosprite.net; www.spritesandjets.com

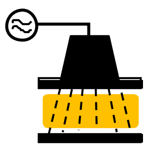
APP in laboratory and industry

Electrical gas discharge
→ high voltage power supply
→ DC, AC, pulsed // frequency: Hz ... MHz
→ electrical breakdown according to Paschen law
(breakdown voltage depend on pressure x distance)



Electromagnetic radiation
→ microwave excited plasmas (915 MHz, 2.54 GHz)
→ ignition structure needed
→ usually “hot” plasmas

Electron beam
→ electron accelerating tubes
(beam gun, keV ... MeV)
→ extensive installations
→ used for flue gas treatment (depollution)



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Incidences of atmospheric plasmas

Nature
- St' Elmos Fire
- Aurora
- Ligthnings
- Transient luminous events

Engineering and Technology
- Partial discharges (electrical engineering)
- Switching
- Welding
- Melting and incineration
- Surface activation
- Chemical conversion
- Ligth emission
- Environmental technology

Research and Development
- Plasma medicine
- Film deposition
- …

High economic impact!

→ Detection/Protection
→ Process optimization
→ Novel Applications

Special features / relevance

- **High density of neutral background gas = high collision rates**
  → rapid breakdown
  → high and rapid mass/energy transfer (heating, chemistry, …)
  → high space charges (causing e.g. instabilities)
  → higher breakdown fields

- **Avoidance of vacuum devices (pumps, chambers, ...)**
  → less cost and maintenance intensive
  → linear throughput processing

- **Several applications require ambient/open conditions**
  → biomedical applications ("Plasma medicine")
  → decontamination of exhaust and flue gases
  → material processing
  → plasma chemistry (3-body collisions)

... but be aware of:
gas consumption; by-products; high voltage, heating, etc. ...

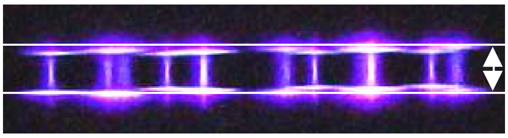
Microdischarges and microplasmas

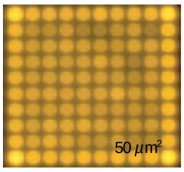
= Discharges with dimensions of µm ... mm

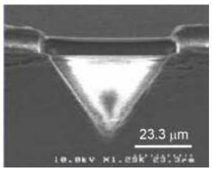
Microplasmas
- Generated in small structures or narrow cavities (e.g. as arrays or in tubes)
- characteristics differ from traditional plasmas at lower pressures

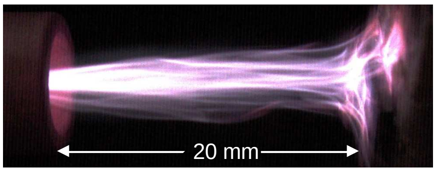
Microdischarges (Filamentary plasmas)
- Formation of fine plasma channels, so-called filamentary discharges

→ Portability and non-equilibrium („cold“) character offer variety of new applications


gap 1 mm



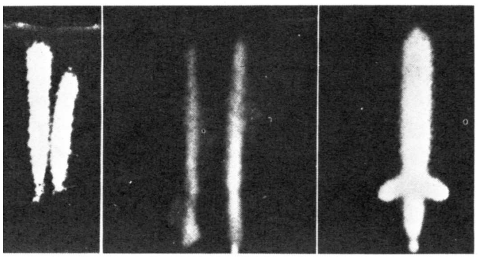




J. G. Eden et al., University of Illinois

Atmospheric plasmas and microplasmas

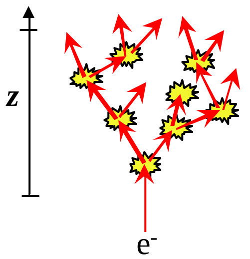
2. Physics of plasmas at atmospheric pressure



Electron avalanches

Ionisation cascade

Townsend-avalanches
John S. Townsend
(1868-1957)



$$N_e = 1e^{\alpha z}$$

$$\nu_i = \alpha v_{D,e}$$

ionisation
electron drift

α 1. Townsend coefficient
ν_i ionisation frequency
$v_{D,e}$ drift velocity of electrons

H. Raether „Electron avalanches and breakdown in gases“ (1964)
Yu.P. Raizer „Gas Discharge Physics, Springer-Verlag, Berlin Heidelberg (1991)

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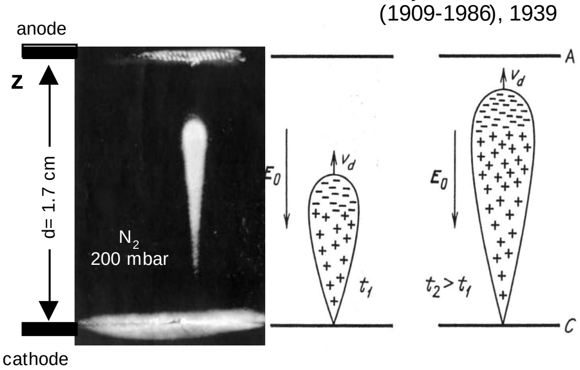
Shape/charge distribution of el. avalanches

Cloud chamber track of a single avalanche by H. A. Raether (1909-1986), 1939



electron/ion mobility: $\mu_e >> \mu_i$

H. Raether „Electron avalanches and breakdown in gases“ (1964)
Yu.P. Raizer „Gas Discharge Physics, Springer-Verlag, Berlin Heidelberg (1991)

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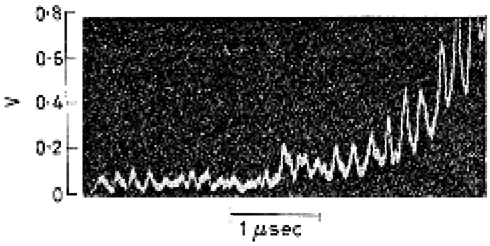
Avalanche breakdown



Series of avalanches lead to breakdown

Figure 3.22. Series of avalanches in room air at U_{ga}, which lead to breakdown; $E/p = 17{\cdot}1$, $p_{0} = 760$ Torr, $d = 3{\cdot}5$ cm. The growth of the current in generations can be observed up to current amplitudes ten times higher than the mean amplitude reproduced here

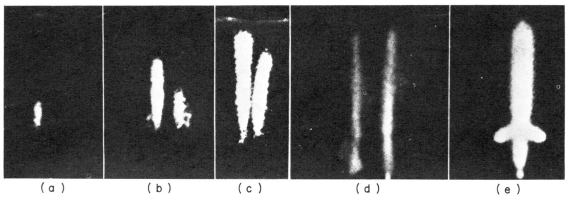


Figure 3.51. Cloud-chamber photographs of electron avalanches and avalanche-streamer transition in a gap of 3·6 cm in air at 260 torr. The field is ~11800 V cm^{-1} in (a) and slightly higher for each successive photograph reaching ~12200 V cm^{-1} in (e) (Raether, 1939. Reproduced by permission of Springer-Verlag)

Avalance-to-streamer transition @ high electric fields and long gaps

H. Raether „Electron avalanches and breakdown in gases" (1964)

Townsend breakdown

- Direct ionisation

$$N_e = N_{e,0}\, e^{\alpha z}$$

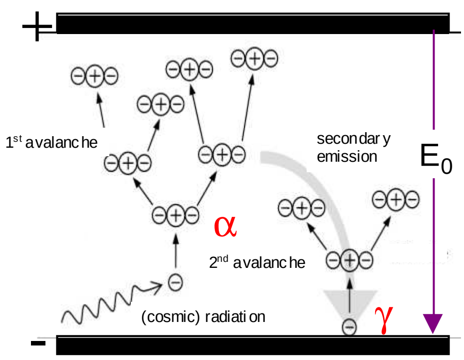
$$\nu_i = \alpha\, v_{D,e}$$

- Secondary electron emission by ion impact

- **Townsend-Criterion:** self-sustained discharge

$$\gamma \cdot \left(e^{\alpha d} - 1\right) = 1$$

$$pd < 1\, bar \cdot cm$$



α	1. Townsend coefficient
ν_i	ionisation frequency
$v_{D,e}$	drift velocity of electrons
γ	3. Townsend coefficient

Streamer breakdown

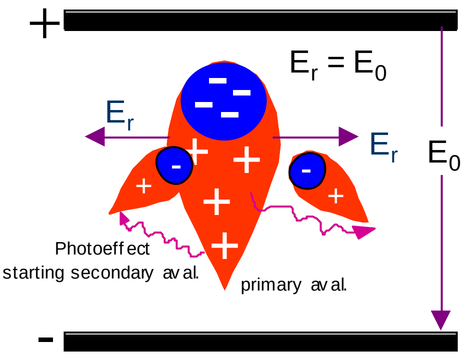
- concept developed by L.B. Loeb; H. Raether; J.M. Meek
- significant field distortion due to space-charge build-up in a single avalanche

$$\mu_e >> \mu_i$$

- formation of thin ionised channel(s)
- Raether-Meek-Criterion

$$e^{\alpha d} \approx 10^8$$

$$\int_0^d \alpha x \, dx = K \approx 18$$



μ_e, μ_i Electron and ion mobility

$$pd > 10\, bar \cdot cm$$

Streamer family

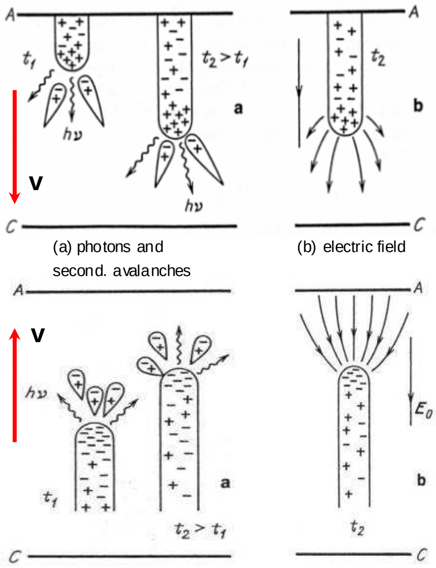
Positive or <u>cathode- directed</u> streamer
(most common)

→ propagating distortion of electric field due to space-charge accumulation

→ secondary avalanches in front of positive streamer end

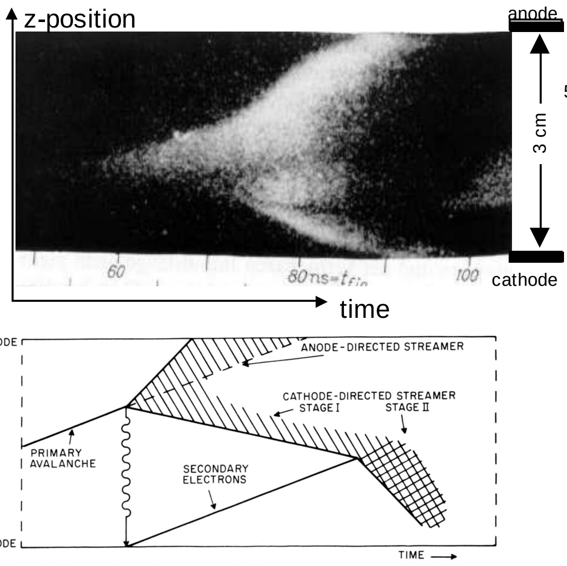
Negative or <u>anode-directed</u> streamer
@ large gaps & overvoltages

→ secondary avalanches in front of negative streamer head



Yu.P. Raizer „Gas Discharge Physics, Springer-Verlag, Berlin Heidelberg (1991)

Streak photo at pre-spark stadium



N_2
500 mbar

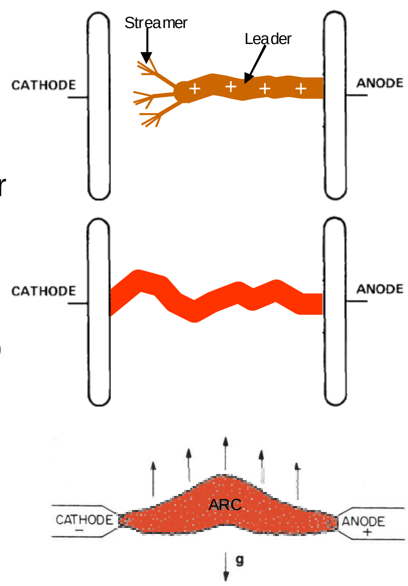
streamer velocities up to 10^6 m/s
(= 10 times $v_{D,e}$)

K.H. Wagner; Zeitschrift fur Physik 204 (1967) 177 / Loeb & Craggs; Wiley 1978

Partial breadkown - leader, spark, arc

P (I)

Streamer
⇩
Leader
⇩
Spark (Lightning)
⇩
Arc



Partial Breakdown
Breakdown
Arcing

Partial breadkown and spark

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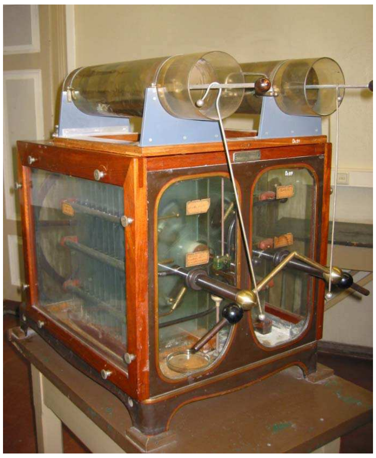
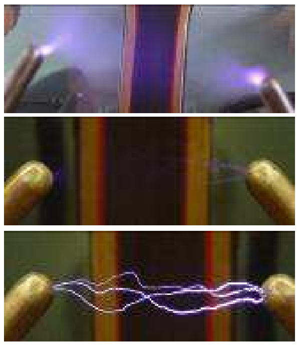


Influenzmaschine; Uni Greifswald

Streamers



Spark

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APP tend to LTE-plasma regime!

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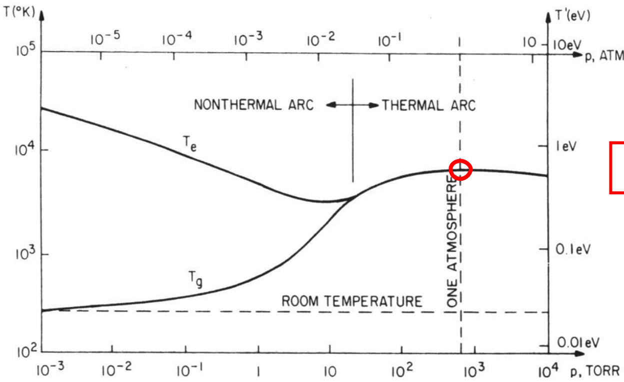
Local Thermal Equilibrium ("thermal")

- microreversibility of elementary processes and equipartition of energy between all species of particles
- "local": long-range effects like radiation not in in thermodynamic equilibrium (Planck's law not valid)



$T_i \approx T_g \approx T_e$

J.R. Roth „Industrial Plasma Engineering", Vol. 1: Principles, IOP Publishing Ltd 1995

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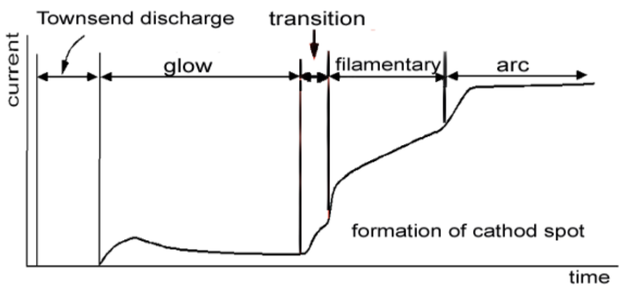
Non-LTE-plasmas at atmospheric pressure

APP are not solely LTE plasmas



Kekez et al. 1970

Mechanismn of glow-to-art transition:
Increase of current density j → increase of local electric field → constriction of ionization channel (filamentation) = increase of j→ cathode spot formation and thermal ionization → thermalization

Limitation of discharge duration (transient)
- Certain number of collisions necessary to establish equil.

Limitation of current / power density
- reduction local dissipated energy density/ electric field

Non-thermal plasma:
$T_e > T_i > T_g$

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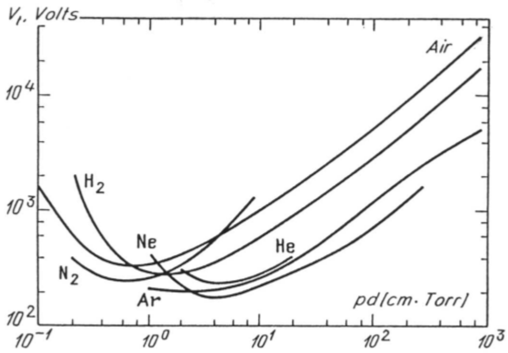
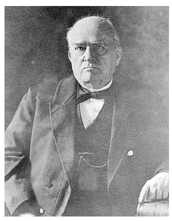
Invariants and scaling

Paschen law $U_{Breakdown} = f(p \cdot d)$





J.W. Hittdorf

$$j/p^2 = const. \qquad \alpha/N = const. \qquad E/N$$

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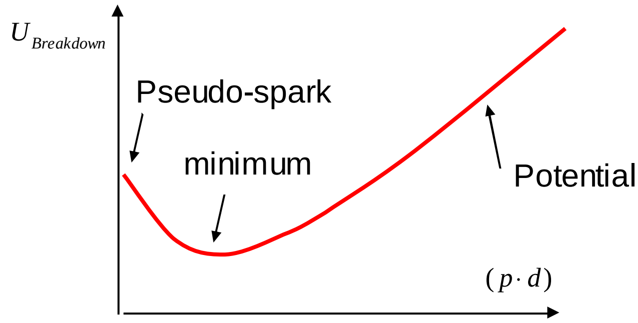
Invariants and scaling

Paschen law $U_{Breakdown} = f(p \cdot d)$



$$j/p^2 = const. \qquad \alpha/N = const. \qquad E/N$$

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Pressure Scaling

$U_{Breakdown} = f(p \cdot d)$

p increase → d decrease	= Miniaturisation

$j/p^2 = const.$

p increase → j constant → r decrease	= Constriction

Limitations:

- 3-body collissions at higher pressures
- High aspect ratios (importance of wall effects like field emission)
- Plasma chemistry
- Instabilities (e.g. glow to arc transition)

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Classification

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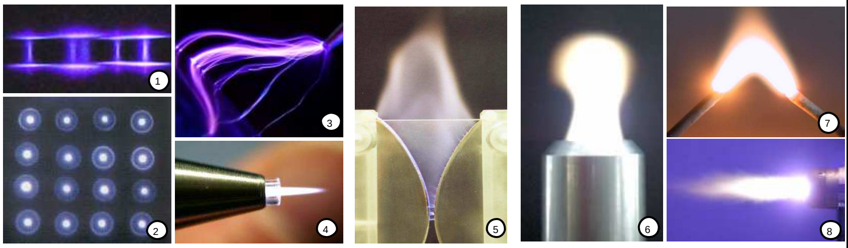
Non-Thermal (NT) Plasmas		Thermal Plasmas
"Cold" Non-Thermal Plasmas	Translational ("Hot NT") Plasmas	Thermal Plasmas
$T_i \approx T_g \approx 300 \dots 400$ K $T_i << T_e < 10^5$ K (10 eV)	$T_i << T_e \leq 10^4 \dots 10^5$ K $T_i \approx T_g \leq 4\ 10^3$ K	$T_i \approx T_g \approx T_e$ $T_x < 5\ 10^3 \dots 10^4$ K

- **Barrier discharges** (1)
- **Coronas** (3)
- **Microplasma-Arrays** (2)
- **Plasma jets** (4)
- **Gliding Arc** (5)
- **Plasma Torch** (6)
- **Microwave Driven Plasmas**
- **Arc** (7)
- **Arc jet** (8)



Atmospheric pressure plasmas

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3. Arc discharges, arc jets, and plasma torches

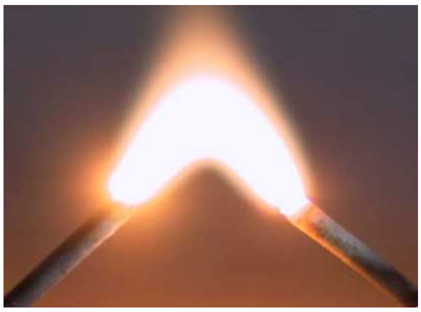
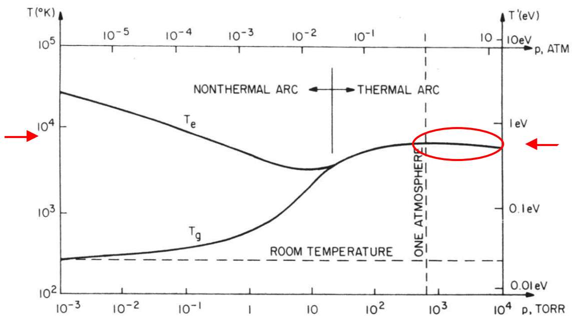


Photo: Achim Grochowski

Arcs at 1 atm: LTE-plasmas!

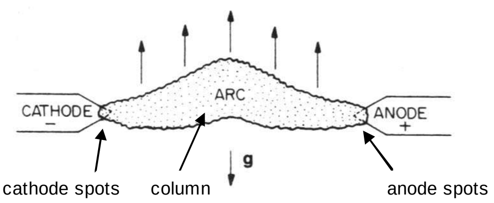


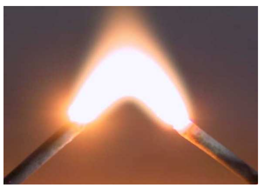
„Thermalization“ due to high density and thus high collision rates

- **LTE: 0.5 eV < $T_e \cong T_g$ < 5 eV** (1eV ≅ 10^4 K); **non-thermal outside the core**
- Arc current: **50 < I < 10^4 A**; Voltage: some **10 V;** Electric field: **500 < E < 5000 V/m**
- Energy density: **10^7 ... 10^9 J/m^3**; Current density: **10^7 < j < 10^9 A/m^2**
- Typical cathode emission: **field emission** and thermionic emission
- Electron density: **10^{22} < n_e < 10^{25} m^{-3}**
- Ionization degree: SAHA equation

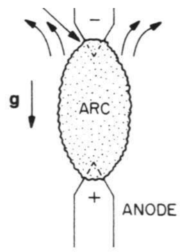
Free-burning arcs / „arc family“

Convective heat transport → „ARC“



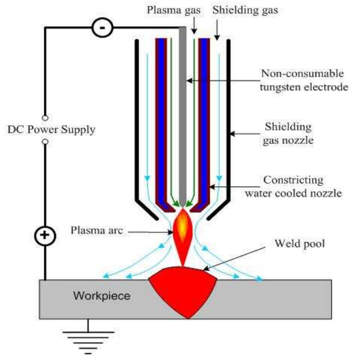


- arcs with hot thermionic cathode
- arcs with external cathode heating
- arcs with cold cathode and cathode spots
- vacuum arc
- high and /or very high -pressure arc
- low pressure arcs
- special modes etc. ...

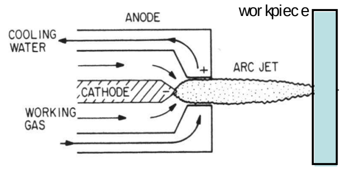


Transferred and non-transferred arc

Transferred Arc
- work piece used as electrode
- mainly used for welding
  (gas tungsten arc welding GTAW; tungsten inert gas TIG; plasma arc welding PAW)
- with shielding gases for special applications



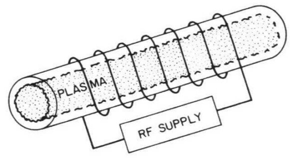
Non-Transferred Arc (Plasma Torch)
- work piece subjected to high-enthalpy plasma flow
- used for spraying and chemistry

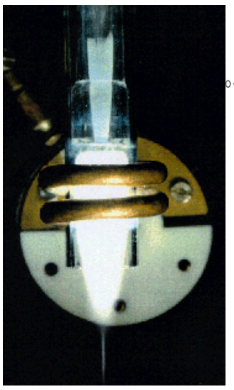


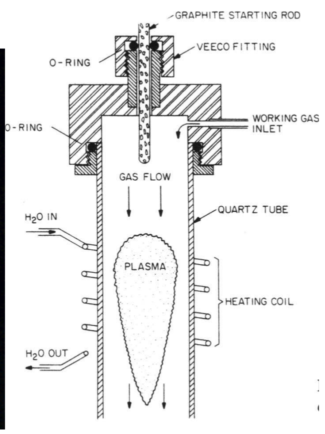
Dmitri Kopeliovich; www.unilim.fr/.../2006limo0029/html/TH.2.html

ICP-Torch

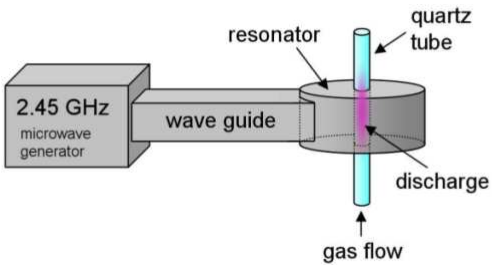
- Inductively Coupled Plasma (ICP): current by transformer action
- Frequency 10 kHz ... 30 MHz (RF)
- Power 1 kW ... 1 MW
- T = 10^3 ... 2 10^4 K







Microwave Induced Plasmas (MIP)

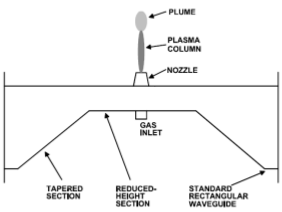


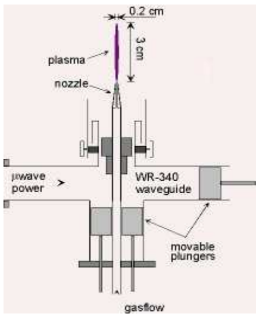
MW Zander

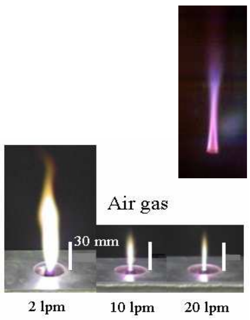
- Resonant cavity plasmas using different kinds of resonators (e.g. round or cylindrical) to induce peaking of field intensity in the center of the resonator

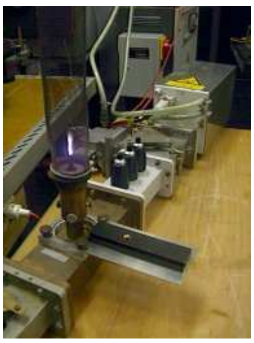
Ehlbeck, Pollack, Winter, et al,. J Phys D 2011

Miniaturized MIP-torches: TIA and TIAGO





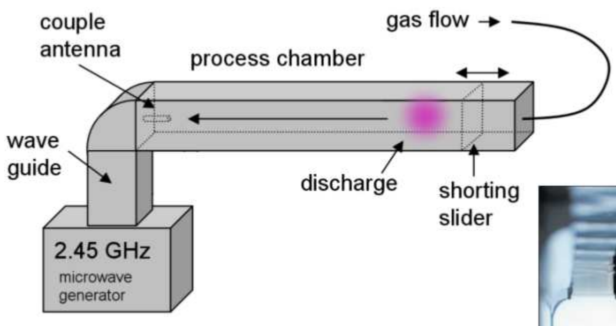




- TIA(GO): torch a injection axial (sur guide donde)
- Surfatron-based coaxial microwave plasma
- Mainly used for spectrochemical analysis applications (atomic emission spectrometry)

M. Moisan et al., Plasma Sources, Sci. and Technol. 3, (1994) and Plasma Sources Sci. Technol. 10 (2001); photos: TU Eindhoven and Y.S.Bae et al. J. Korean Phys. Soc. 48, 1 (2006)

Microwave Induced Plasmas (MIP)



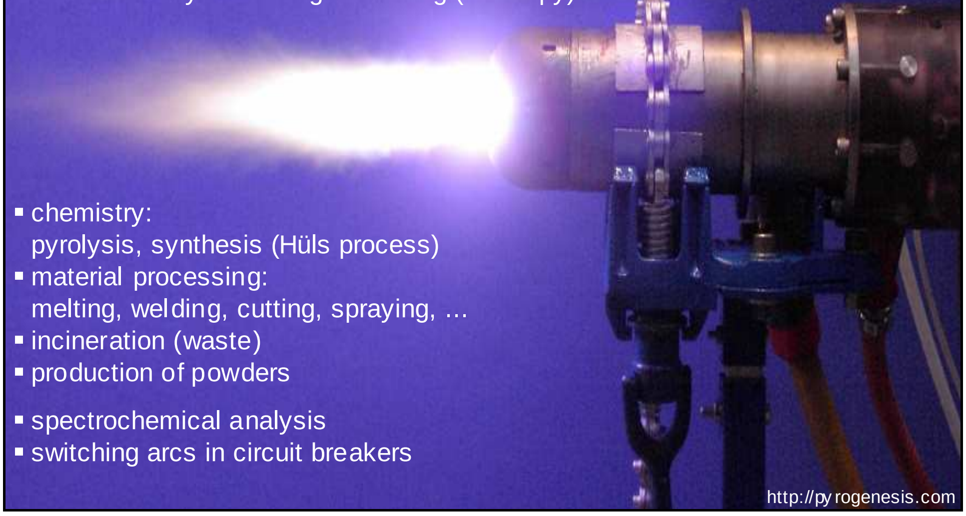
Ehlbeck, Pollack, Winter, et al,. J Phys D 2011

J. Ehlbeck et al. GMS Krankenhaushyg. Interdiszip 3 (2008)

INP Greifswald

Arc and torch applications

Arcs: Thermal plasmas
Arc-jets & Torches: Thermal or translational plasma („Hot non-thermal“)
→ Most widely used for gas heating (Enthalpy)

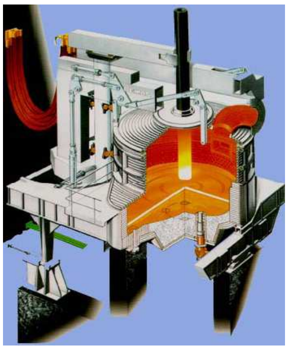


- chemistry:
  pyrolysis, synthesis (Hüls process)
- material processing:
  melting, welding, cutting, spraying, ...
- incineration (waste)
- production of powders
- spectrochemical analysis
- switching arcs in circuit breakers

http://pyrogenesis.com

Arc melting / steel making / metallurgy

Electric Arc Furnace (EAF)



- up to 100 MW active power
- 600 … 320 kWh/t
- graphite electrodes (60 … 80 cm diameter)
- 140 kA (dc); 75 kA (ac)

D. Neuschitz, RWTH Aachen

Plasma spraying of bone implants

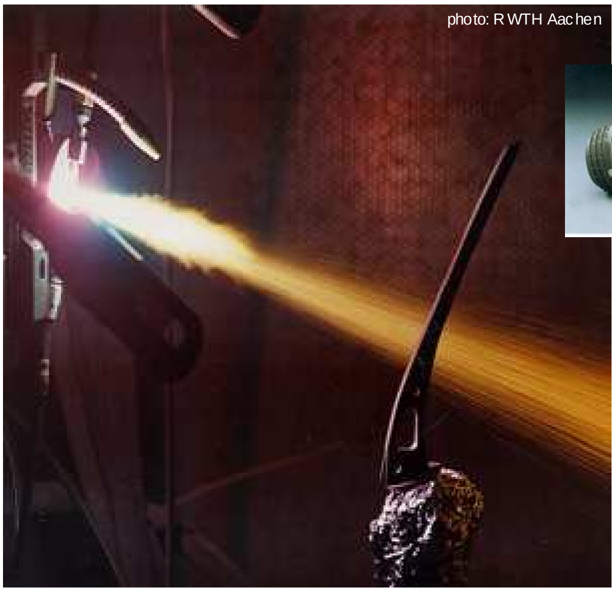


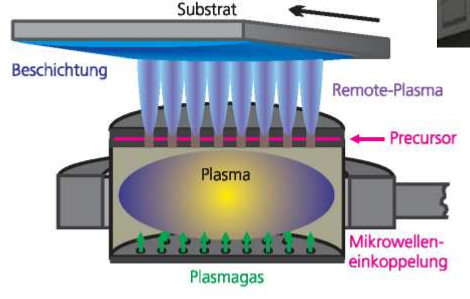
photo: RWTH Aachen

photo: MAT, Dresden

Surface processing by MIP-remote

Atmospheric pressure chemical vapour deposition (AP-PECVD)

Cyrannus Plasma Source (iplas)
(5 … 10 kW; 50 … 200 slm Ar)



- c-Si Photovoltaik
- etching, texturing
- SiN_x:H

V. Hopfe, I. Dani et al. Fh-IWS Dresden / iplas / Universität der Bundeswehr

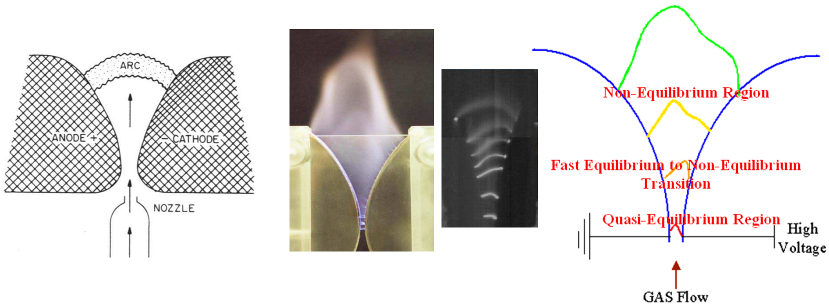
Plasma sound-sources: Plasma tweeter

- sound emission by gas heating: compression wave (comp.lightning and thunder)
- amplitude modulated plasma power by audio signals vary plasma intensity and thus create compression waves
- perfect „point-sound“ sources (Tweeter: high frequencies)

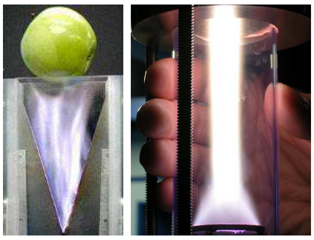
- Plasma arc loudspeaker, plasma ion tweeters or flame speakers

http://www.plasmatweeter.de/

Gliding arc principle („Jacobs ladder“)



- arc (or spark) discharge in non-perpendicular discharge gap
- expansion cooling → non-thermal
- investigations on surface processing and volume chemistry (e.g. CH_4 conversion)

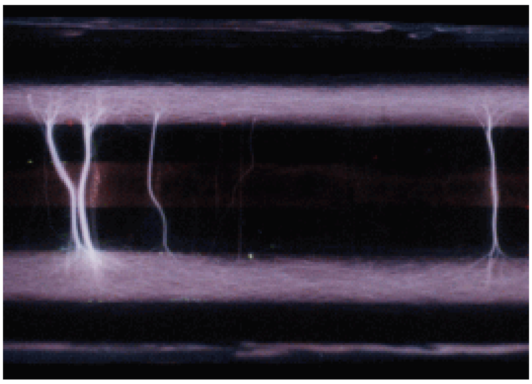


A. Gutsol et al.; Drexel University

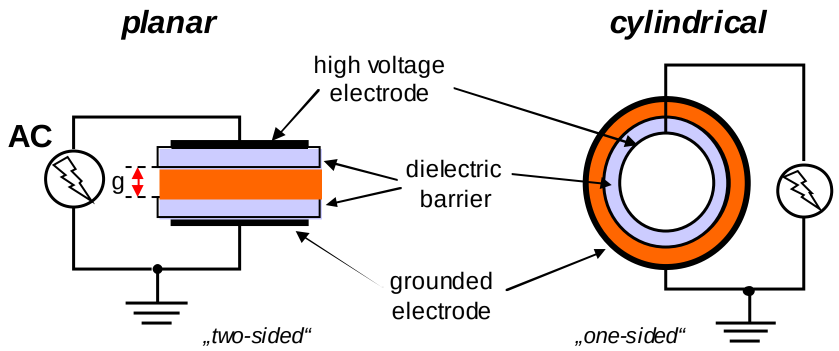
Atmospheric plasmas and microplasmas

4. Barrier Discharges

(Silent Discharges; Dielectric Barrier Discharge)

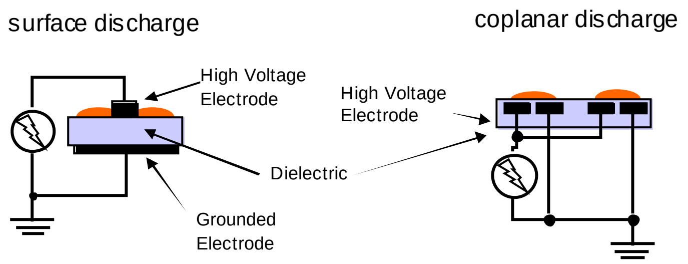


Volume discharges



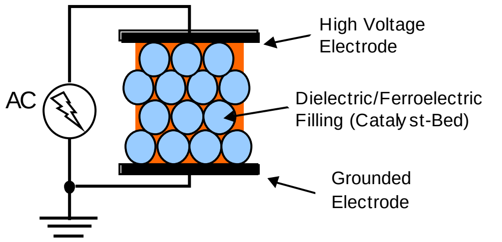
p = 0.5 ... 3 bar
V_{pp} = 3 ... 20 kV; f = 50 Hz ... 100 kHz
g = 0.2 ... 5 mm; ε_r = 5 ... 10 ... 10^4 (dielectric ... ferroelectric)

Surface and coplanar discharge

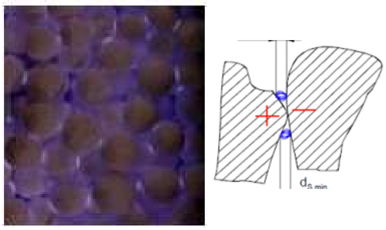


Packed-bed reactors

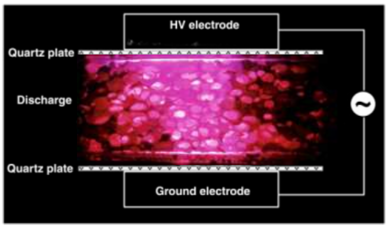
packed bed reactor (Mizuno, Yamamoto et al.)



Pellet filling

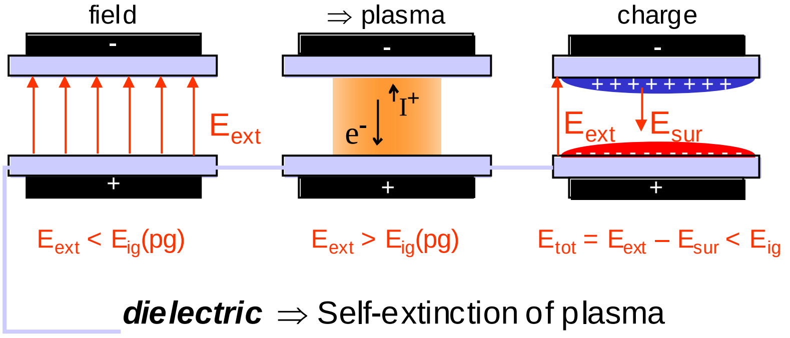


Ceramic foam filling



Pictures: McAdam/Electroca; Holzer/UFZ; Krauss/ABB

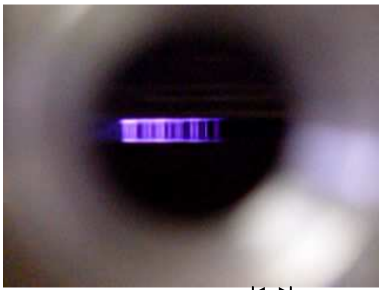
Role of the dielectric

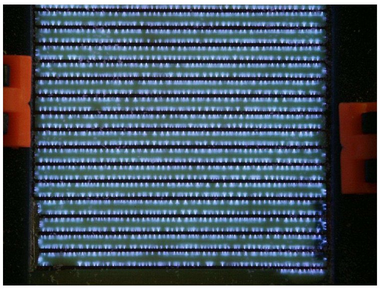


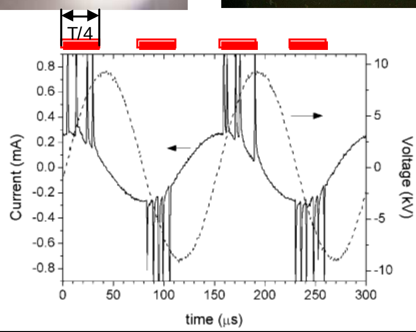
dielectric barrier ⇒ Self-extinction of plasma
⇒ Limitation of dissipated energy

Prevention of sparking / arcing
⇒ non-thermal plasma!

Filamentary plasmas

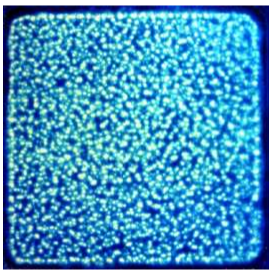


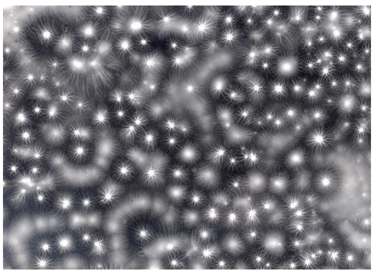




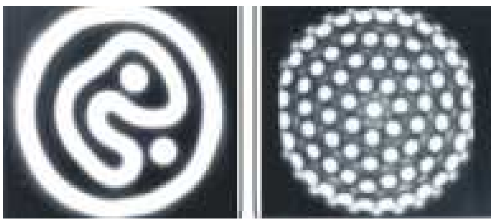
Filamentary structures

MD footprints (Lichtenberg figures)





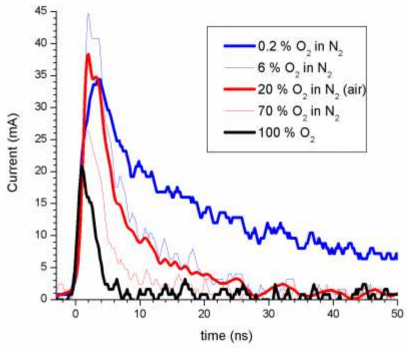
Regular MD-pattern

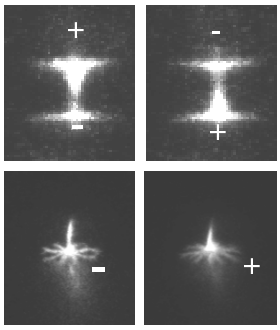


U. Kogelschatz ABB Switzerland; Purwins et al., Uni Münster

Microdischarge properties

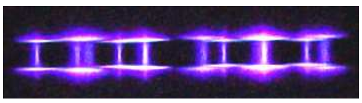
▪ duration:	1-10 ns
▪ radius:	0.1 mm
▪ transported charge:	100-1000 pC
▪ current density:	100-1000 A cm^2
▪ concentration of electrons:	10^{14} bis 10^{15} cm^3
▪ averaged energy of electrons:	1-10 eV
▪ gas temperature:	near room (cold)



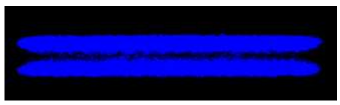


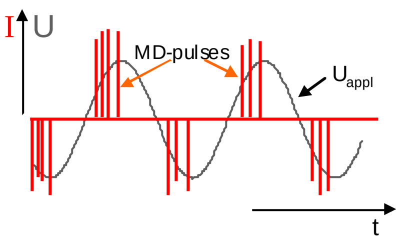
Diffuse vs. filamentary BDs

Filamentary

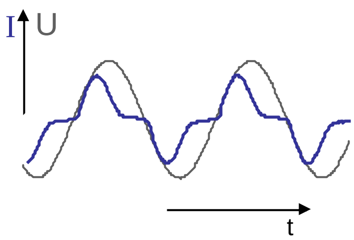


Diffuse





statistical MDs, ns-range

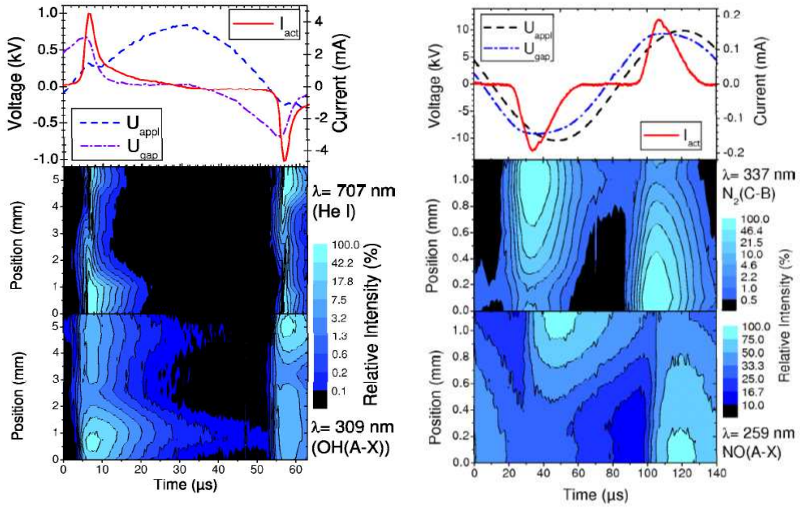


periodical (appl. frequency)
µs-range

Diffuse BDs (APGD; APTD)

Atmospheric pressure glow discharge
He, Ne, Ar/NH_3; $j^{max} \approx 1$ mA/cm²

Atmospheric pressure Townsend discharge
N_2; $j^{max} \approx 0.1$ mA/cm²



Z. Navratil et al.; Plasma Sources Sci. Technol., 15 (2006), 8-17
R. Brandenburg et al., J. Phys. D: Appl. Phys., 38, 13 (2005), 2187-2197

Preventing filamentation

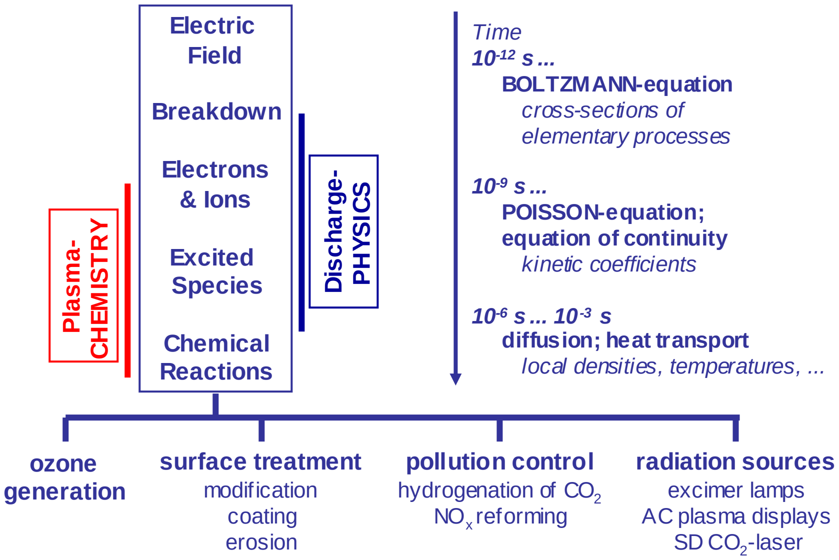
by gas mixture:
- minimum initial electron density and ionization rate before breakdown
  → pre-ionisation by x-rays or second discharge
- supression of rapid ionization during breakdown
  → minimum dU/dt
  → minimum $\delta(\alpha/N)/\delta(E/N)$ (best in case of helium!)
- indirect ionisation processes (e.g. Penning-ionisation)
  → slow-down of ionization/breakdown

by geometry/materials
- residual density of ions and excited species (e.g. metastable states)
- surface properties: γ, ε, σ, humidity, ...

by power control
- Short pulsed plasmas (ns-range)
- Matching of external circuit parameters
- Resistive barrier material

U. Kogelschatz IEEE Trans. Plasma Sci. (2002)

General principle and major applications



Ozone synthesis

O_3: important oxidant

- water cleaning (advanced oxidation)
- paper bleaching

- ozone can't be stored → "on-site" production
- high pressure but low temperature required

1. Dissociation of O_2

$e + O_2 \rightarrow O^- + O$

$\rightarrow O + O + e$

$\rightarrow O + O^* + e$

$e + N_2 \rightarrow N_2^* + e$

$N_2^* + O_2 \rightarrow N_2 + 2O$

2. Formation of O_3

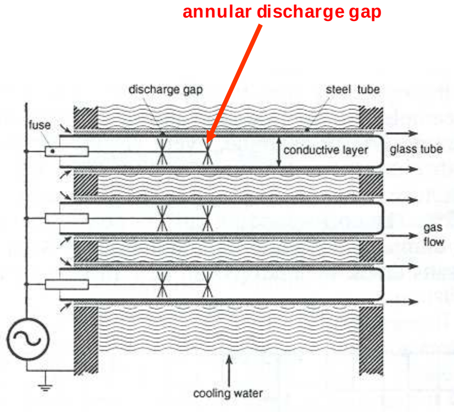
$O + O_2 + M \rightarrow O_3 + M$

($M = N_2, O_2$)

Ozone yield (g/kWh)	Oxygen	Air
Sinusoidal voltage	150 … 180	80 … 95
Impulse voltage (kV/ns)	240 … 290	130 … 140
Theoretical limit	430 … 450	200 … 220

Largest facility in Brazil: 500 kg/h

Modern Ozonizers



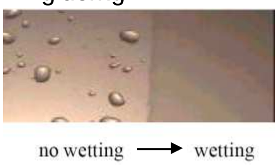
U. Kogelschatz et. al; Journal de Physique **7** (1997) C4-47

Surface „Corona“ treatment

Activation to change surface energy / wettability or Coating

- printing
- glueing

on polymers, textiles, ...

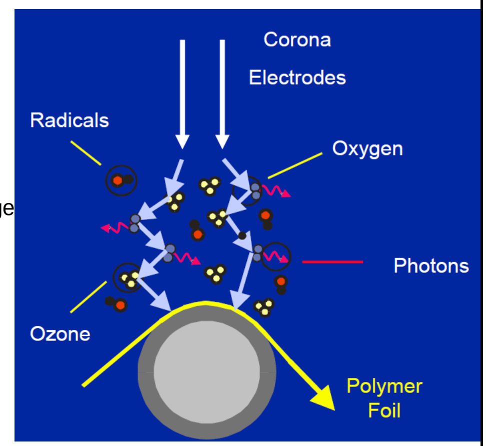


Activation:

- electrons cause chain breakage
- incorporation of polar groups and other functional groups

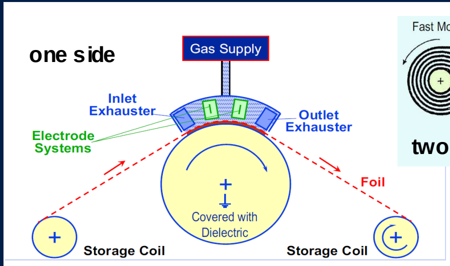
Coating (Aldyne):

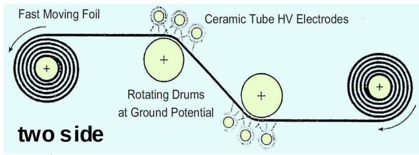
- admixture of precursors (ppm of silane)



figures: tigres GmbH; softal GmbH

Corona stations

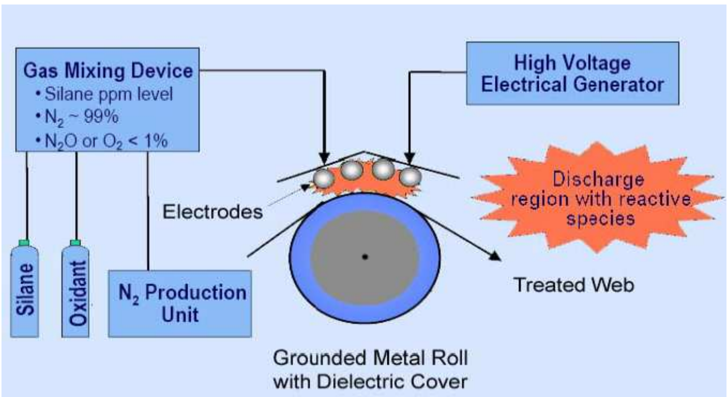




- web speed: 10 – 200 m/min
- residence time: a few seconds
- energy deposition: 0.1 – 1.0 J/cm^2

U. Kogelschatz, J. Salge in „Low Temperature Plasma Physics" Wiley-VCH Berlin (2001)

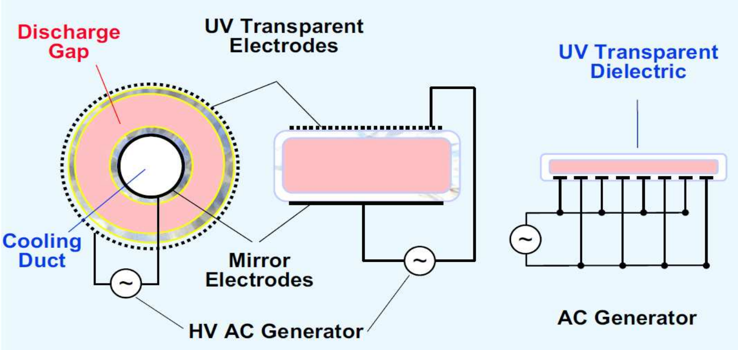
Aldyne process

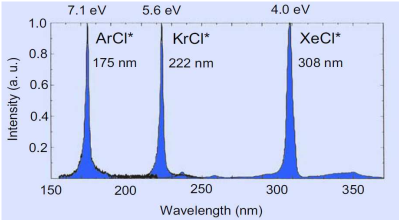


- Silane-Precursor: reactive molecular layer which form stable chemical bonds with commercial inks (varnishes water-based, solvent-based or UV-curable)
- Applications: Labels; Flexible packaging (food and non food); Tapes markets, Graphic arts (Primer free UV Offset Printing and gluing of CPP packaging); Flooring / Coverings

L'Air Liquide/Softal

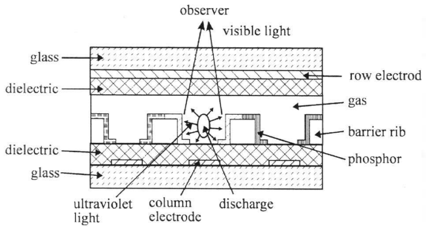
Excimer lamps

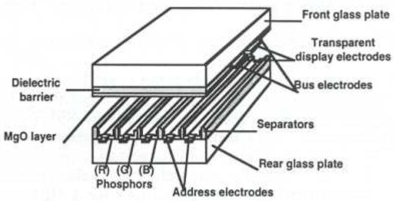




- UV curing in web and sheet offset press
- UV printing
- Photolytic structured metal deposition
- Room temperature oxidation of silicon

Plasma displays

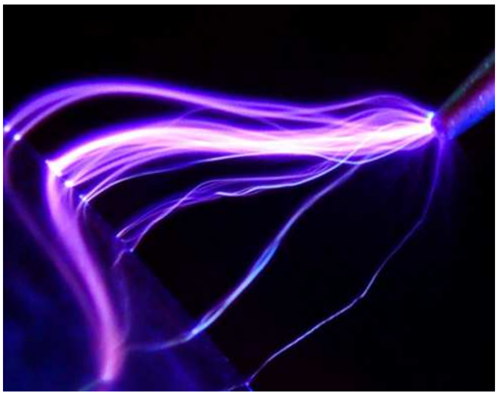




Panasonic (2008): Largest Plasmadisplay 3.81 m (150 Zoll) diagonal/ 8.84 Megapixel

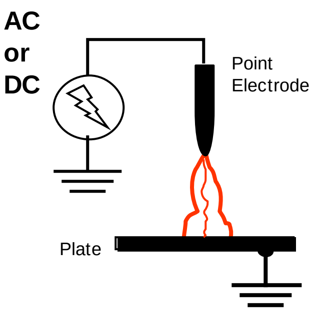
Atmospheric pressure plasmas

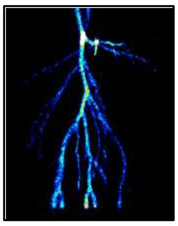
5. Corona Discharges



http://www.dpchallenge.com/

Principle / geometry

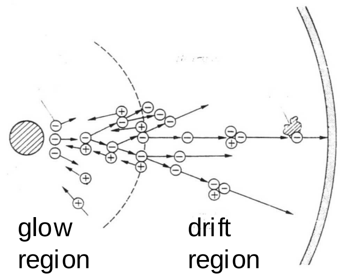




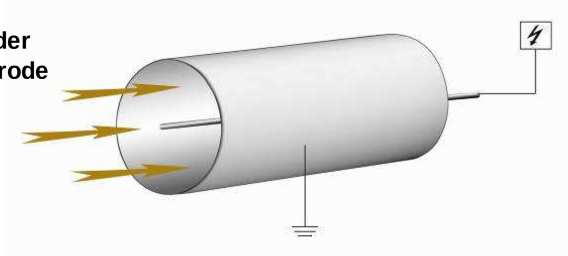
Point-to-plane or wire

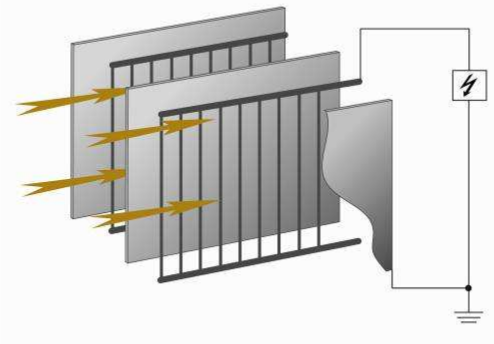
-

non-uniform electric field



Corona discharge





INP Greifswald

Corona onset – Peek‘ law

$$E_c = 30\,\delta \left[1 + \frac{0.3}{(\delta R)^{1/2}} \right]$$

$\delta = N / N_0$
R = Wire Radius

$$M = \exp\left(\int (\alpha - \eta) dx\right) = 10^4$$

$M \approx 3 \cdot 10^4$ Townsend-Breakdown

$M = 10^8$ Streamer-Breakdown

an explanation for the low magnitude of Q. We conclude that the most likely cause of the low value of Q is the onset of indirect ionization processes, such as from metastable–metastable collisions, which then enables the discharge to be maintained at a value of E/N significantly lower than the critical E/N for which ionization equals attachment.

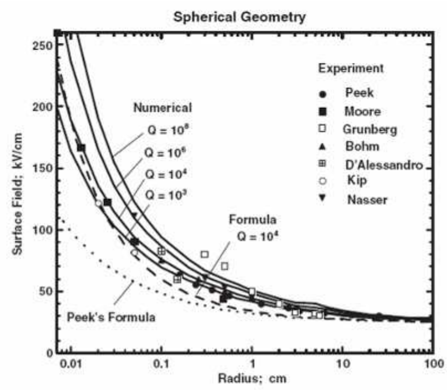
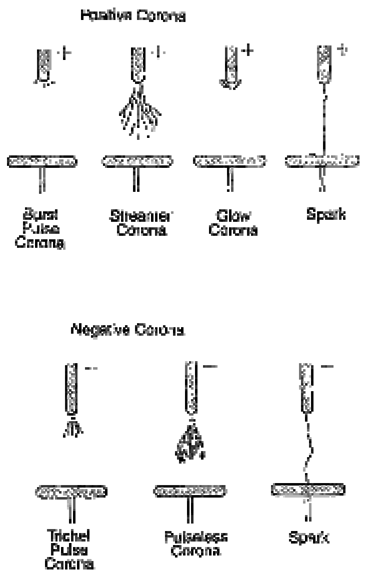


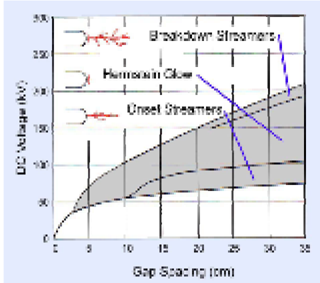
Figure 4. Experimental data points for corona onset from points and spheres as a function of point radius. Also shown as curves are theoretical predictions obtained numerically and also from predictions using Peek's formula for wires, equation (1), and the formula given by equation (7).

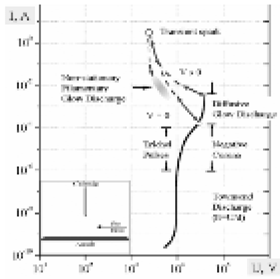
J.J. Lowke and F. D‘Alessandro J. Phys. D: Appl. Phys. 36 (2003) 2673-2682

INP Greifswald

Modes of corona discharges

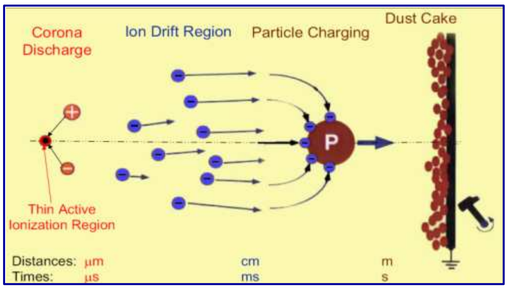




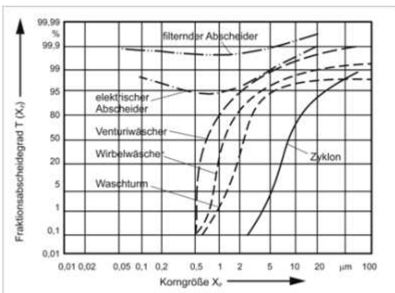


Chang et al. IEEE Trans. Plasma Sci. ***19****(1991)*

Electrostatic precipitators



- Voltage: 30–80 kV
- Down to 1 µm diameter
- Up to 300.000 Nm³/h

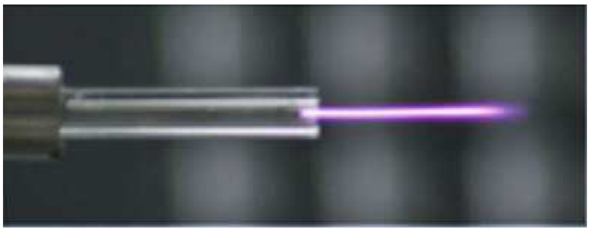


M. Bank „Basiswissen Umwelttechnik“ 2006

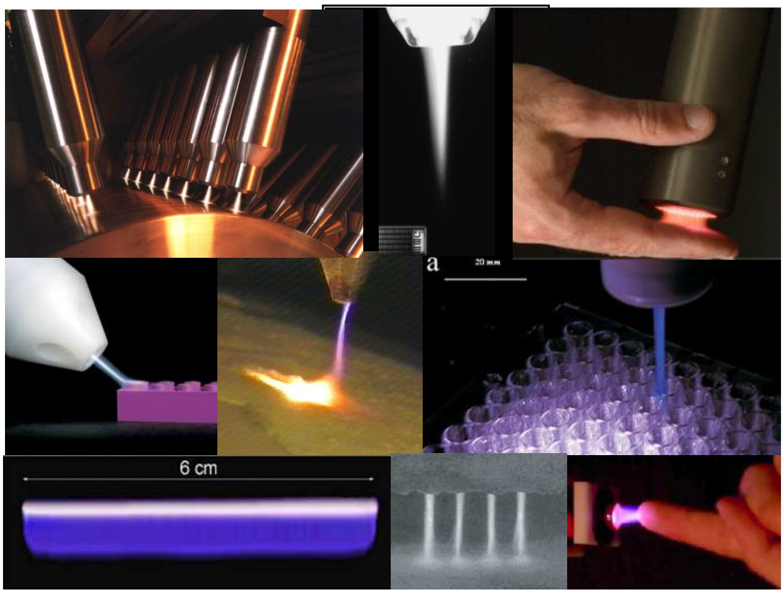
ABB

Atmospheric pressure plasmas

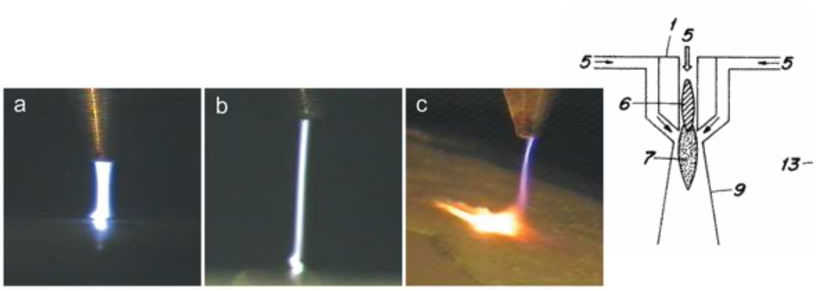
6. Plasma jets



Diversity in design, operation ...



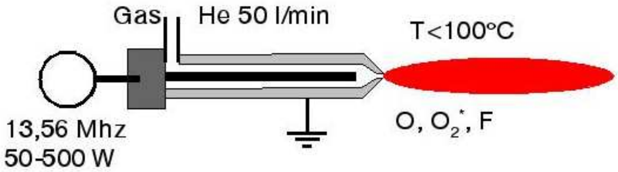
Plasma pencil (1997)



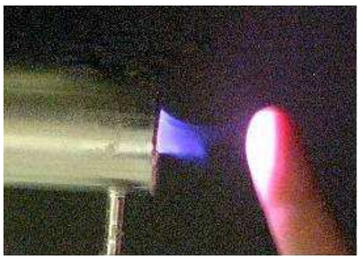
M. Klíma, J. Janča, V. Kapička, P. Slavíček, A. Brablec and others

APPJ - Atmospheric pressure plasma jet

Selwyn et al; Los Alamos National Laboratory

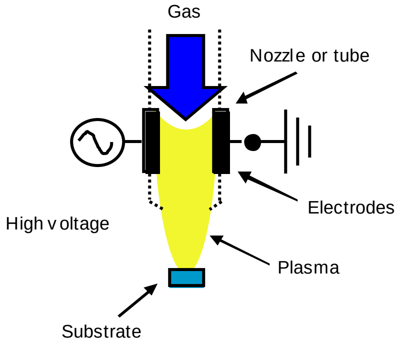


Helium:
>> low breakdown voltage
>> high heat conductivity



A. Schuetze et al., IEEE Trans. Plas. Technol. 26 (1998)

Plasma jet principle



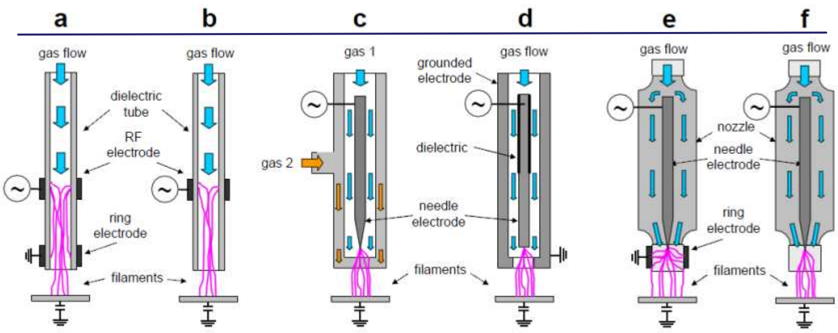
“Gas flow transports plasma outside electrode configuration”

- non-thermal plasmas
- pulsed dc ... GHz
- Power 1 ... 1 kW

“Remote-type”
- active plasma between electrodes
- plasma jet = effluent or afterglow (long lived species)
- potential free

“Active-type”
- active plasma between electrodes and between nozzle and substrate
- plasma jet contains free electrons
- current transport through substrate

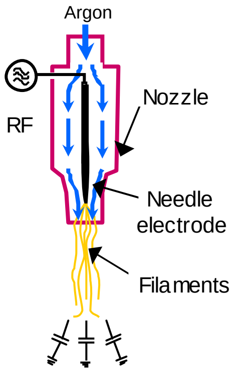
Plasma jet configurations

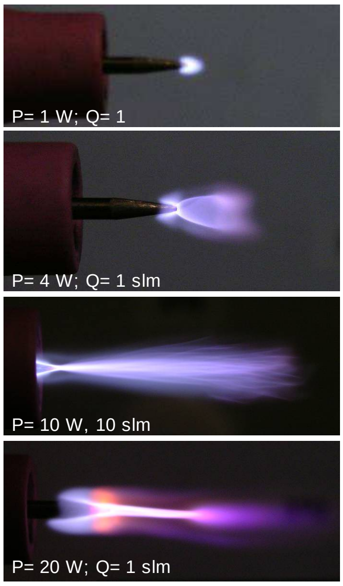


a) using 1 powered and 1 grounded ring electrode
b) without grounded ring electrode
c) combination of 2 tubes whereas the inner tube is streamed with a noble gas for discharge ignition and the outer tube with a precursor
d) composed of two coaxial electrodes with a dielectric in between
e) consisting of an inner RF driven needle electrode and a grounded ring electrode
f) without grounded ring electrode

Ehlbeck, Pollack, Winter, et al,. J Phys D 2011

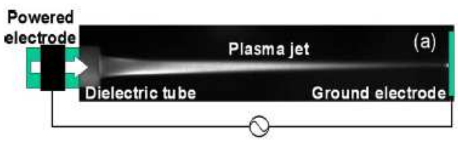
Turbulent „active plasma“ jet

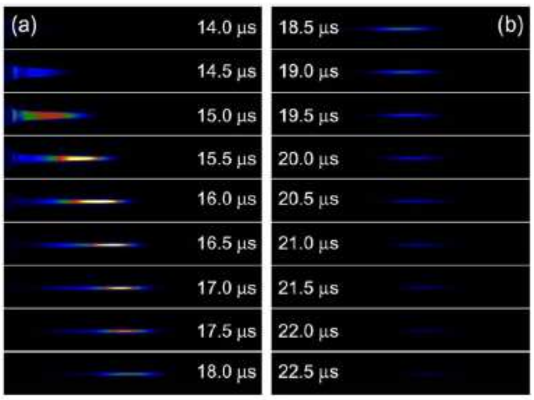




- Active, filamentary plasma
- cooling and expansion by argon-gasflow
- jet operates in it's “own” atmosphere

Plasma bullets (noble gases)

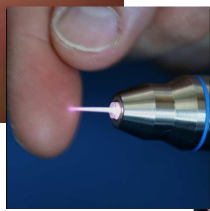




- hypersonic train of plasma bullets
- travelling ionisation fronts

J. Shi et al; Phys. Plasmas **15**, 013504 2008

kINPen

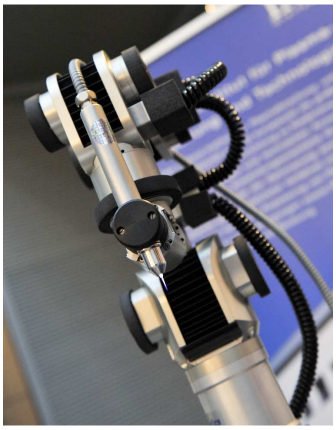


- $P = 5 \ldots 40$ W
- $f = 13$ MHz / 27 MHz
- gas: Argon, N_2, ….
- $Q = 1 \ldots 20$ slm

- compact and modular
- low power consumption
- penetrates in small structures
- non-thermal plasma

R. Foest et al., Plasma Phys. Control. Fusion 47 (2005) B525-B536

Treatment of complex workpieces

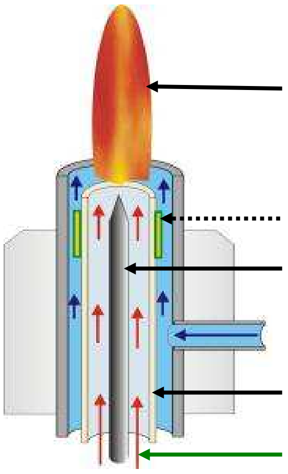


kiNPen Plasma jet

neoplas tools

Configuration with precursor admixture

INP Greifswald

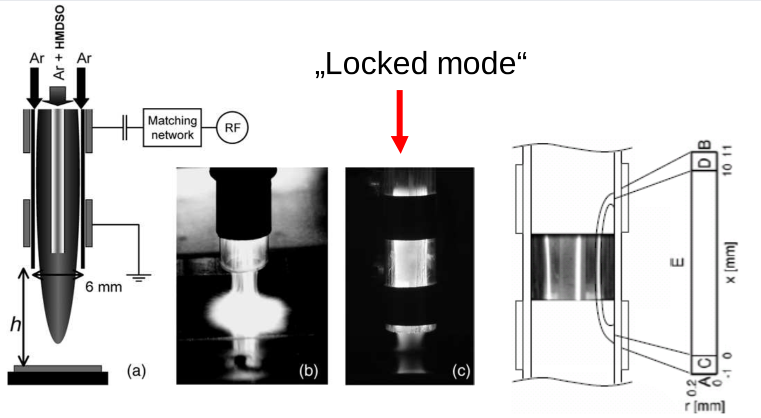


INP Greifswald

Self organized plasma jet

INP Greifswald

„Locked mode"

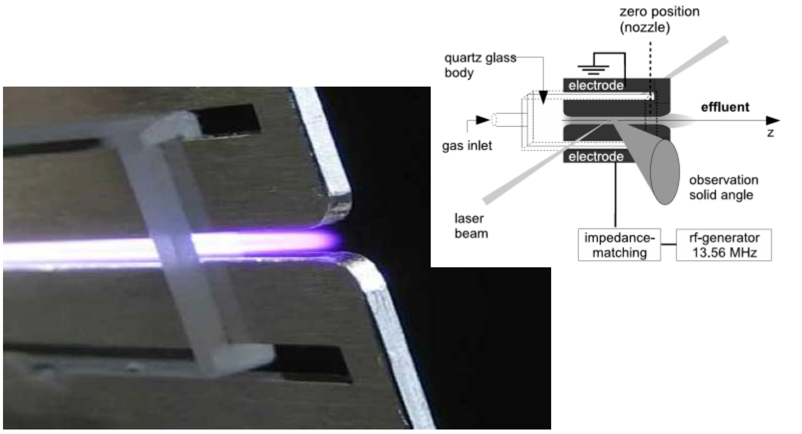


- quasi-laminar flow: controlled number of equidistant filaments which rotate regularly with constant frequency at inner wall of outer capillary
- distinctive discharge regime of plasma jet which produces a foot print of discharge symmetric with respect to the axis
- Ultimately leads to an enhanced homogeneity of deposited SiO_x-films

INP Greifswald

J. Schäfer, Eur. Phys. J. D **60**, 531–538 (2010); J. Phys. D: Appl. Phys. 41 (2008) 194010

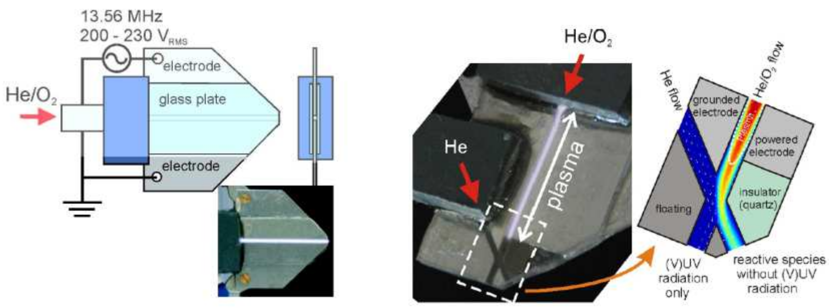
µ-APPJ (RF-driven; He, Ar)



- α-mode: dominated by ionization processes in the bulk
- γ-mode: secondary electron emissions from electrode surface

V. Schulz-von der Gathen, S. Reuter et al. (RU Bochum / Uni. Essen)

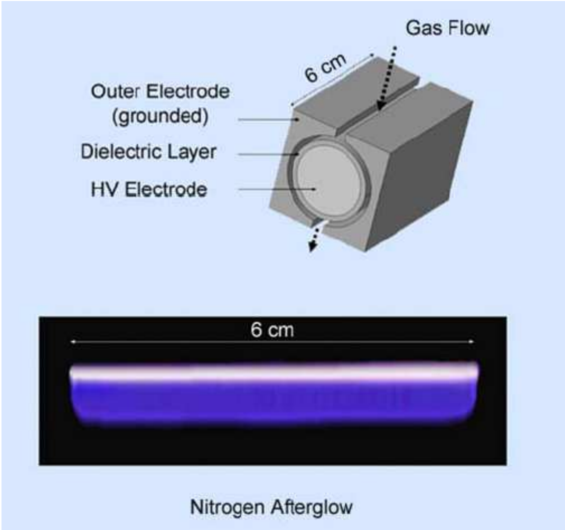
µ-APPJ and X-jet



- additional helium flow steers flow of radical species into side channel
- Separation of (V)UV radiation and reactive species

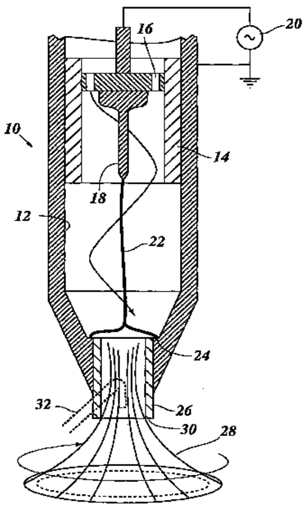
J. Benedikt, S, Schneider et al. (RU Bochum)

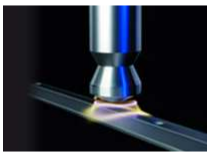
Linear plasma jet source



AcXys

Openair-Plasma (Plamatreat)

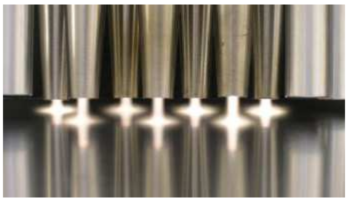




Plasmatreat

Plasma and Corona treaters

Plasma-Blaster

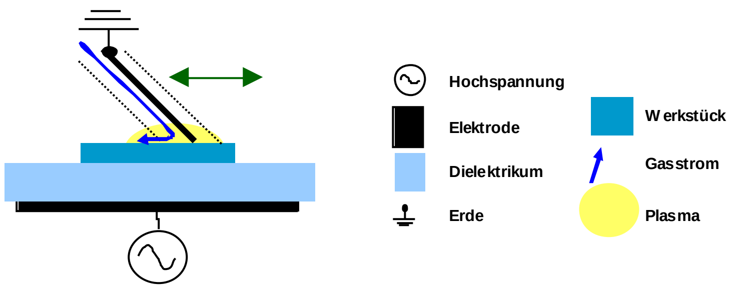


„Korona-GUN“

Change of surface energy to improve adhesion

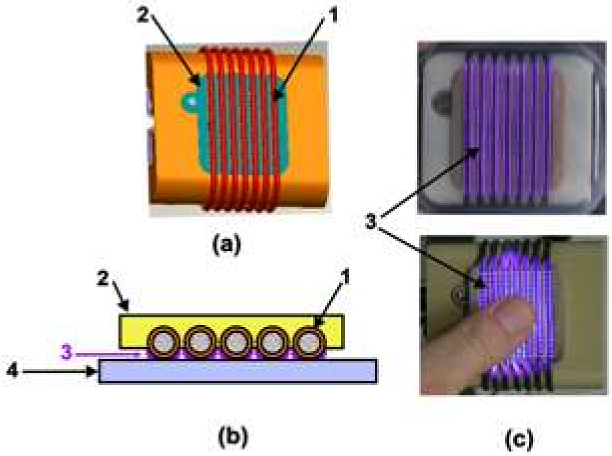
Dr. Gerstenberg GmbH Tigres

New concept: Conplas



Plasma source ConPlas®

INP Greifswald



Functional principle of the plasma source ConPlas®: (a) 3D-CAD model and (b) schematic side view of the plasma handheld unit, (c) plasma unit of a lab prototype in operation; 1 - isolated wires as high voltage electrodes, 2 - grounded electrode, (3) - plasma, (4) - object to be treated

INP Greifswald

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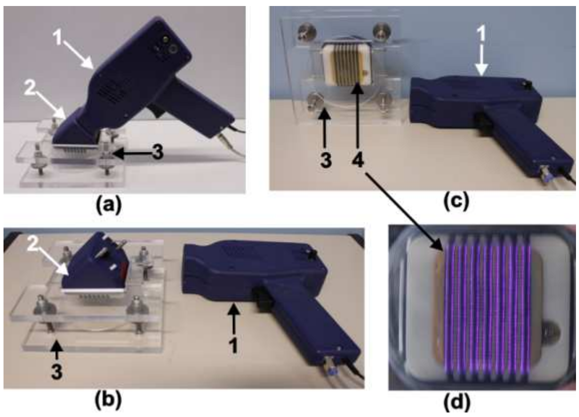
ConPlas® hand-held lab prototype

INP Greifswald



Experimental setup with ConPlas® hand-held lab prototype: (a) complete treatment unit, (b) and (c) parts of the hand-held lab prototype separated from one another in different views, (d) plasma unit in operation; 1 - hand-held part with incorporated high voltage power supply, 2 – inter-changeable plasma unit, 3 - adjustable adapter between plasma unit and sample holder, 4 - plasma unit in operation

INP Greifswald

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Plasma jet applications

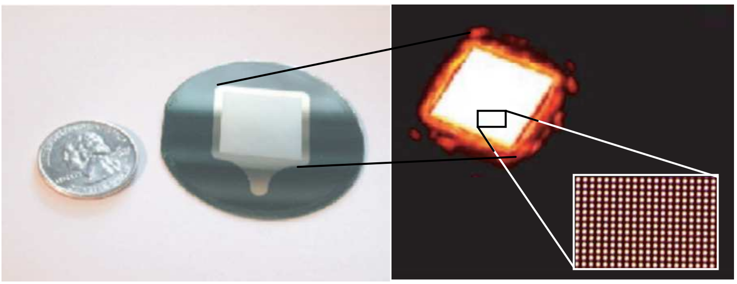
Surface treatment
- Pretreatment prior to painting, printing, bonding, …
  = Cleaning, Activation, Functionalization
- Coating (protective, functionalizing, ..)
- Etching

Detection
- Emission sources for analytic devices

Plasma life-science applications
- Biological decontamination („Sterilization“)
- Therapeutic applications (Plasma medicine)

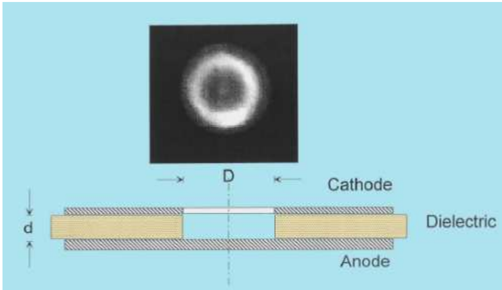
Atmospheric pressure plasmas

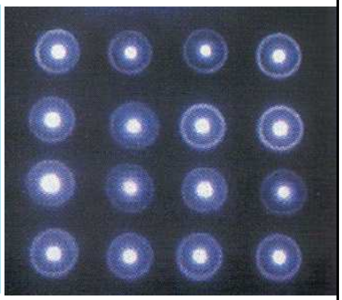
7. Microplasma arrays



pictures composed from: G. Eden et al.; J. Phys. D: Appl. Phys. 38 (2005) 1644–1648

Microhollow cathode discharges (MHC)



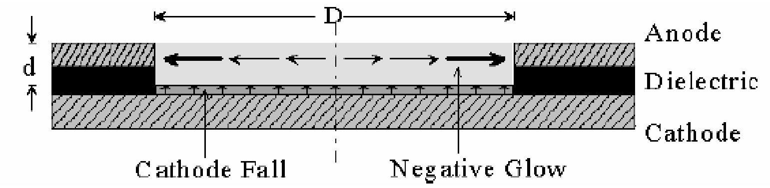


D: 0.1 … 0.25 mm **d about 150 µm**

- MHC concept extends hollow cathode discharge operation to atmospheric pressure
- nonequilibrium plasma (T_g about 2000 K, n_e: 10^{15}cm^{-3} … 5 10^{16}cm^{-3}; T_e: 0.5 – 5 eV)
- many similarities with a glow discharges (thin localized cathode fall region; moderate gas temperature)

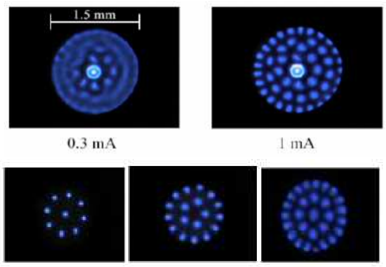
K.H. Schoenbach et al. Appl. Phys. Lett. **68** 1, 13-15 (1996)

Cathode boundary layer (CBL)



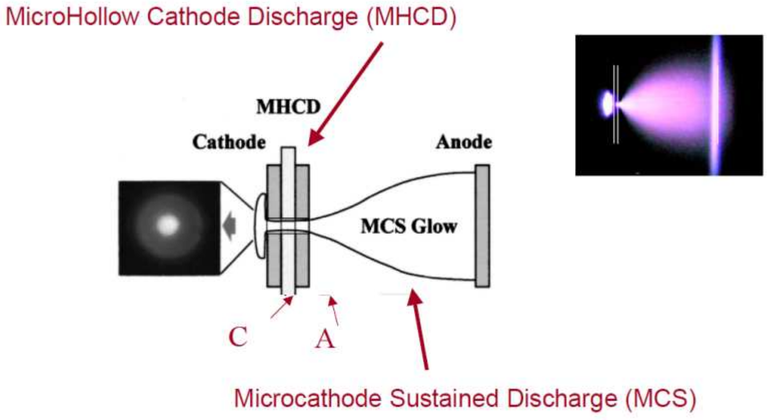
D about 1.5 mm **d about 150 µm**

- hole diameter D of MHC widened to about 1.5 mm
- varying number of self-organized bright discharge spots, originating in the cathode fall region



K.H. Schoenbach et al. Plasma Sources Sci. Technol. 13, 177-185

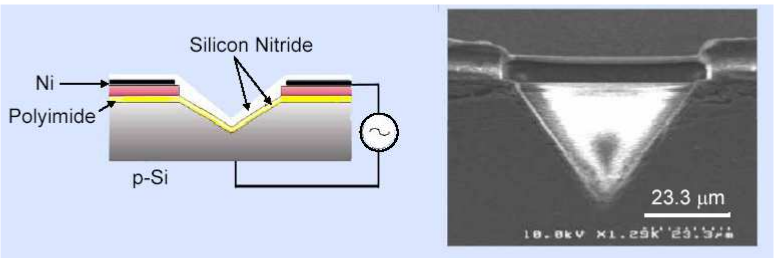
MHCD as plasma cathode



R.H. Stark and K.H. Schoenbach, JAP **85**, 2075 (1999).

One of the best characterized plasma source (Puech, Graham, …)
→ metastables densities, simulations, …

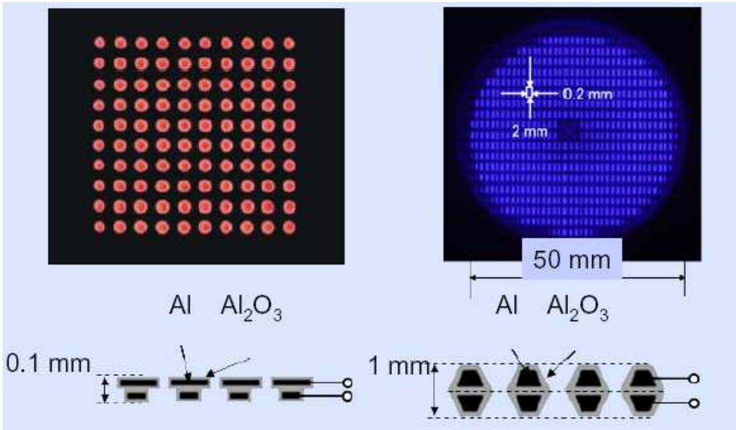
Pyramidal barrier discharge



- use of p-type Si(100) wafers
- micromachining technologies: lithographical patterning; anisotropic wet etching or reactive ion etching
- area of inverted pyramids: 100 x 100 µm^2 down to 10 x 10 µm^2
- flexible arrays possible
- specific local power loading up to 250 kW cm^{-3}

J. G. Eden et al., J. Phys. D: Appl. Phys. **36**(2003), 2869

Microplasma arrays

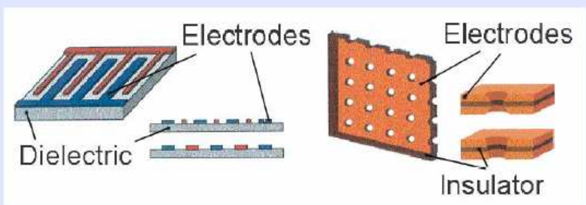


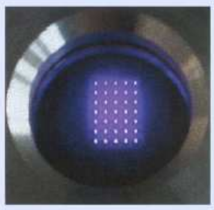
- Al foils or Al structures that can be covered with a thin alumina coating serving as a dielectric layer, e.g perforated 70 µm thick Al foils with Al_2O_3 films of 10 µm thickness

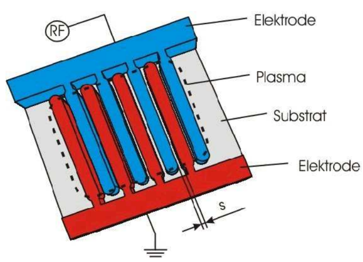
S.-J. Park et al. Appl. Phys. Lett. **86**, (2005);
K. Tachibana et al. Plasma Phys. Control. Fusion **47**, (2005)

RF-capacitively coupled microplasmas

Micro-Structured Electrode Arrays (MSEs)

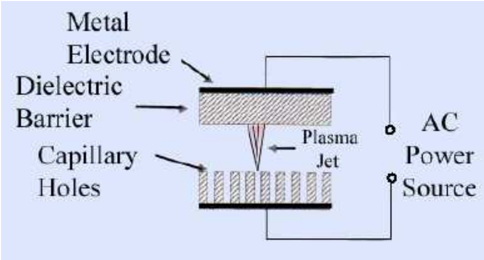


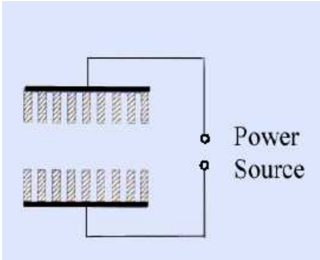




M. C. Penache Penache, Ph.D. Thesis, U of Frankfurt 2002; N. Lucas et al. IMT Braunschweig

Capillary plasma electrode discharge



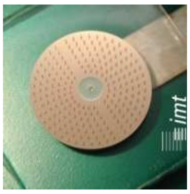


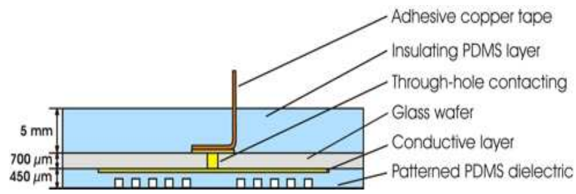
- one or both dielectric plates with parallel thin capillary channels
- frequency above a few kHz: sudden, capillary plasma jets emerge from capillary holes, overlaping and merging to a volume plasma with electron densities by orders of magnitude higher then those observed in diffuse BDs
- each hole acts as a current limiting micro-channel preventing overall current density from increasing above threshold for glow-to-arc transition.

E. E. Kunhardt IEEE Trans. Plasma Sci. **28**(2000), 189 - 200

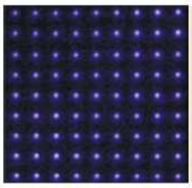
Plasma stamps

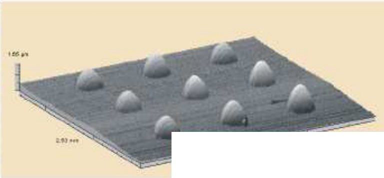
Microstructured Surface Treatment
- micron-scale area-selective surface modification processes
- BD-principle: patterned / structured dielectric
- structure size: 150 … 500 µm





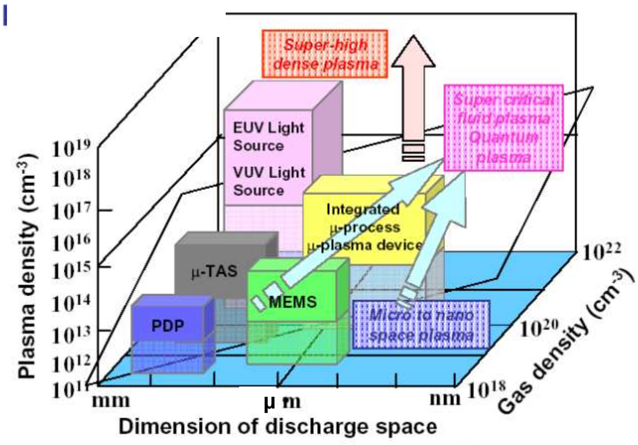
(PDMS: poly-dimethylsiloxane)





N. Lucas, C.-P. Klages et al.; Proc. 3rd Int. l Workshop on Microplasmas, Greifswald, 2006, p. 180-183; Proc. 5th euspen Int. Conference, Montpellier/France, 2005, vol. 2, p. 665-668.

New Applications

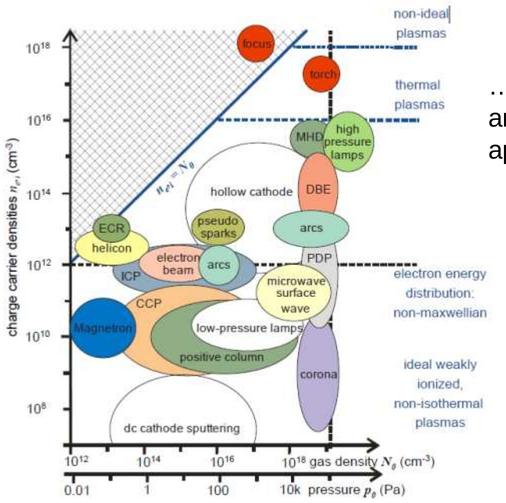


PDP **Plasma Display Panels**
MEMS **Micro ElectroMechanical Systems**
TAS **Total Analytic Systems**

Tachibana, Kyoto University; IEEJ Trans. 2006; 1: 145-155

Resumé

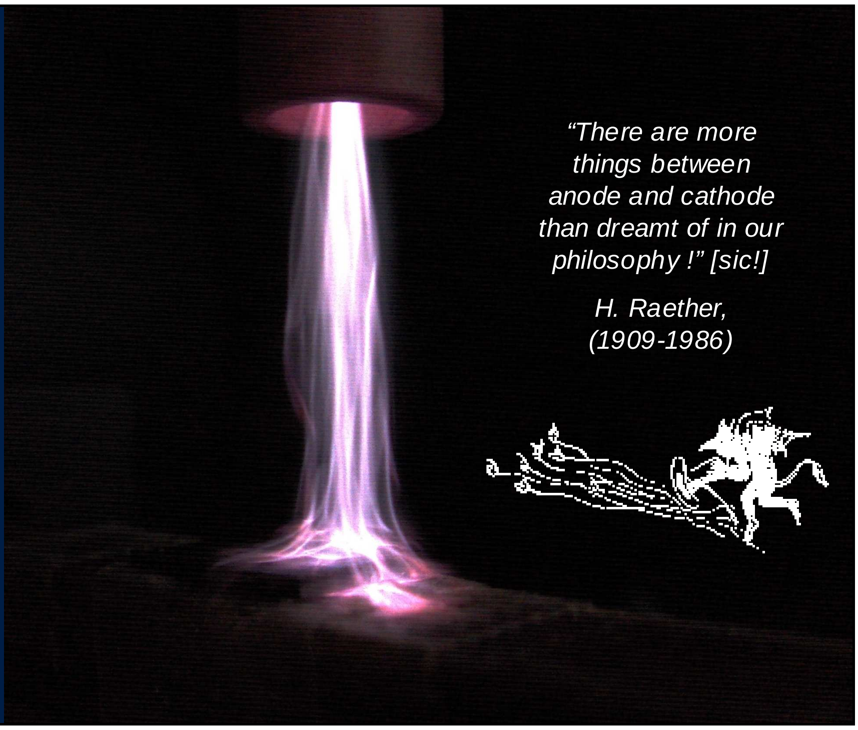
Atmospheric pressure plasmas exist in a wide range of parameters (LTE and non-LTE) and configurations ...



... with many possible and established applications.

„reactive" neutral-dominated plasmas

Picture: H. Kersten, Uni Kiel



INP Greifswald

Atomspheric plasmas and microplasmas

INP

Further reading

„Non-equilibrium air plasmas at atmospheric pressures“ eds. K.H. Becker, U. Kogelschatz, K. H. Schoenbach, R.J. Barker; Institute of Physics Publishing: London (2005), Distributor: Francis & Taylor, CRC Press

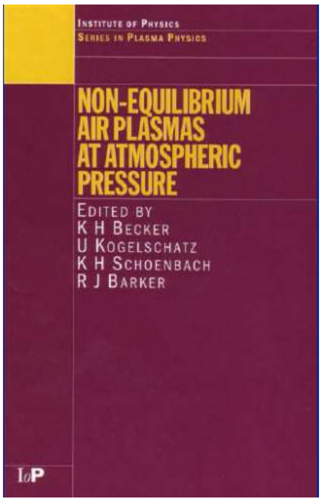
„Electrical breakdown of gases“ eds. J.M. Meek, J.D. Craggs; John Wiley & Sons: Brisbane (1978)

„Fundamentals of gaseous ionization and plasma electronics“ E. Nasser; Wiley-Interscience: New York (1971)

„Plasma chemistry‘ A. Friedman; Wiley-Interscience: New York (1971)

„Gas discharge physics“ Yu.P. Raizer; Springer-Verlag: Berlin (1991)

J.R. Roth „Industrial Plasma Engineering”, Vol. 1 and 2, IOP Publishing Ltd 1995



INP Greifswald

Atomspheric plasmas and microplasmas

Further reading

U. Kogelschatz: "Atmospheric-pressure plasma technology" Plasma Phys. Control Fusion 46, 2004; B63-B75

A. Fridman, A. Chirokov, A. Gutsol : "Non-thermal atmospheric pressure discharges" J. Phys. D- Appl. Phys. 38, 2005; R1-R24

H.-E. Wagner, R. Brandenburg, K.V. Kozlov et al "The barrier discharge: basic properties and applications to surface treatment" VACUUM 71, 3, 2003; 417-436

M. Laroussi and : "Arc-Free Atmospheric Pressure Cold Plasma Jets: A Review" Plasma Proc. and Polymers 2007, 4, 777–788 DOI: 10.1002/ppap.200700066

E. E. Kunhardt "Generation of large-volume, atmospheric-pressure, nonequilibrium plasmas IEEE TRANSACTIONS ON PLASMA SCIENCE, 28, 1, 2000; 189-200

K. Tachibana: "Current status of microplasma research" IEEJ Trans. 2006; 1: 145-155

F. Iza et al.: "Microplasmas: Sources, particle kinetics, and biomedical applications" Plasma Proc. and Polymers 2008; DOI: 10.1002/ppap.200700162

U. Kogelschatz: "Applications of Microplasmas and Microreactor Technology"; Contrib. Plasma Phys. 47, No. 1-2, 80 – 88 (2007) / DOI 10.1002/ctpp.200710012