Electric field behaviour of a micro cavity plasma array (MCPA) measured by Stark shift of helium

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Working group

SFB 1316 Transient Atmospheric Plasmas
from plasmas to liquids to solids

subproject A6 → Pulsed plasma interaction with catalytic surfaces within micro-structured array devices

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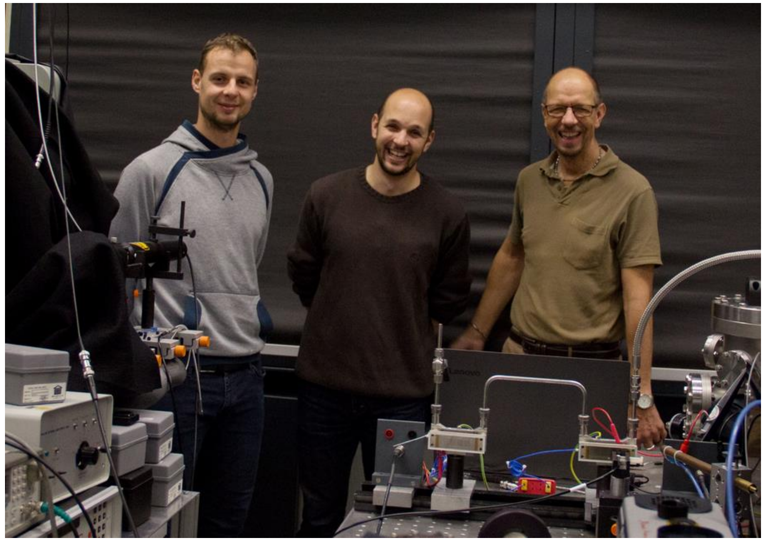


Dr. S. Iseni
GREMI, Orleans

What is a micro cavity plasma array?

- An symmetric and uniform assembly of hundreds to thousands cavities
- Cavities: Dimensions in the micrometer range (~100µm)
- Different shapes (quadratic, cylindrical, inverted pyramidal,…)

- Cavities can be engraved in various wafer (silicon, glass, ceramic, …)

- All cavities are operated with the same excitation

  → Discharge in the cavities can be compared

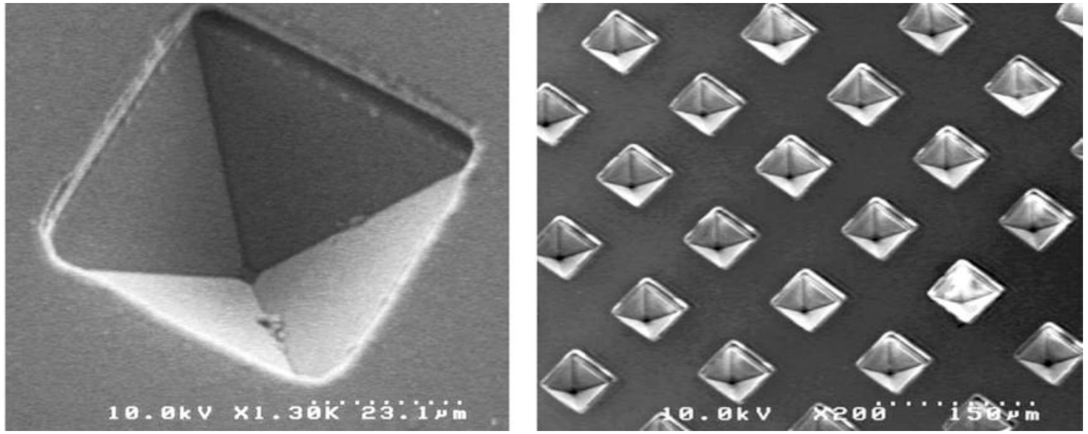


Fig.1) SEMs of a single cavity and a segment of an array with inverted pyramidal cavities

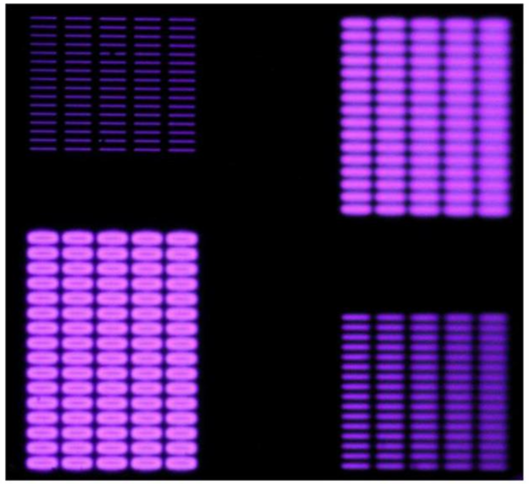


Fig.2) Photograph of a silicon-based array with four different cavity structures DBD [2]

[1] G. Eden et al. J. Phys. D: Appl. Phys. 38 (2005) 1644-1648
[2] M. K. Kulsreshath et al. Plasma Sources Sci. Technol. 23 045012 (2014)

Silicon-based array devices

- Developed by group of G. Eden [2]
- Silicon-wafer contains an array of cavities

- Silicon-based devices are produced by micro-structure technique
  →Integration and subsequent analysis of individual components are difficult

- Measurements with very changeable conditions (pressure, admixture,…)
  →These devices reach their limits
  →Long-term spectroscopy is not possible

- Is there an alternative?

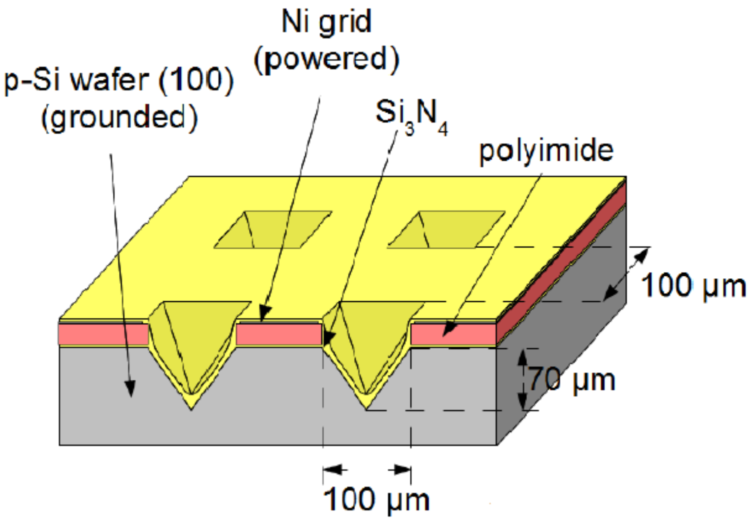


Fig.3) Sketch of a silicon-based array device developed by G. Eden [1]

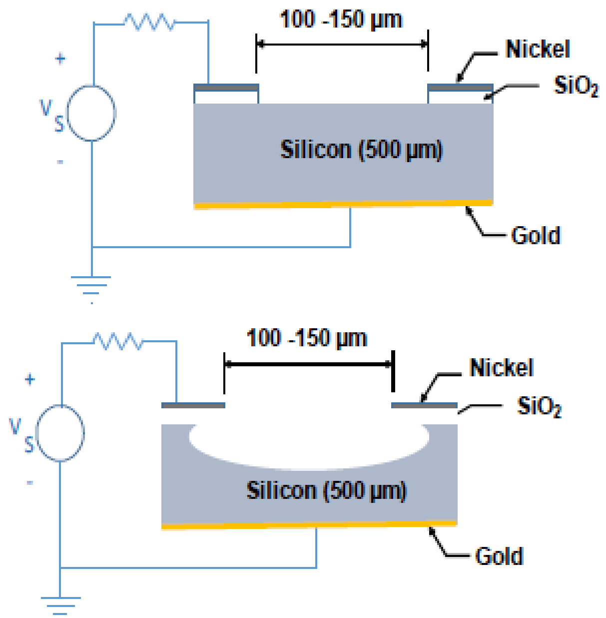


Fig.4) Sketch of a silicon-based array device developed at GREMI in France [3]

[1] G. Eden et al. J. Phys. D: Appl. Phys. 38 (2005) 1644-1648
[3] R. Michaud et al. Plasma source Science and Technology 24 (2018)

Metal-grid array device

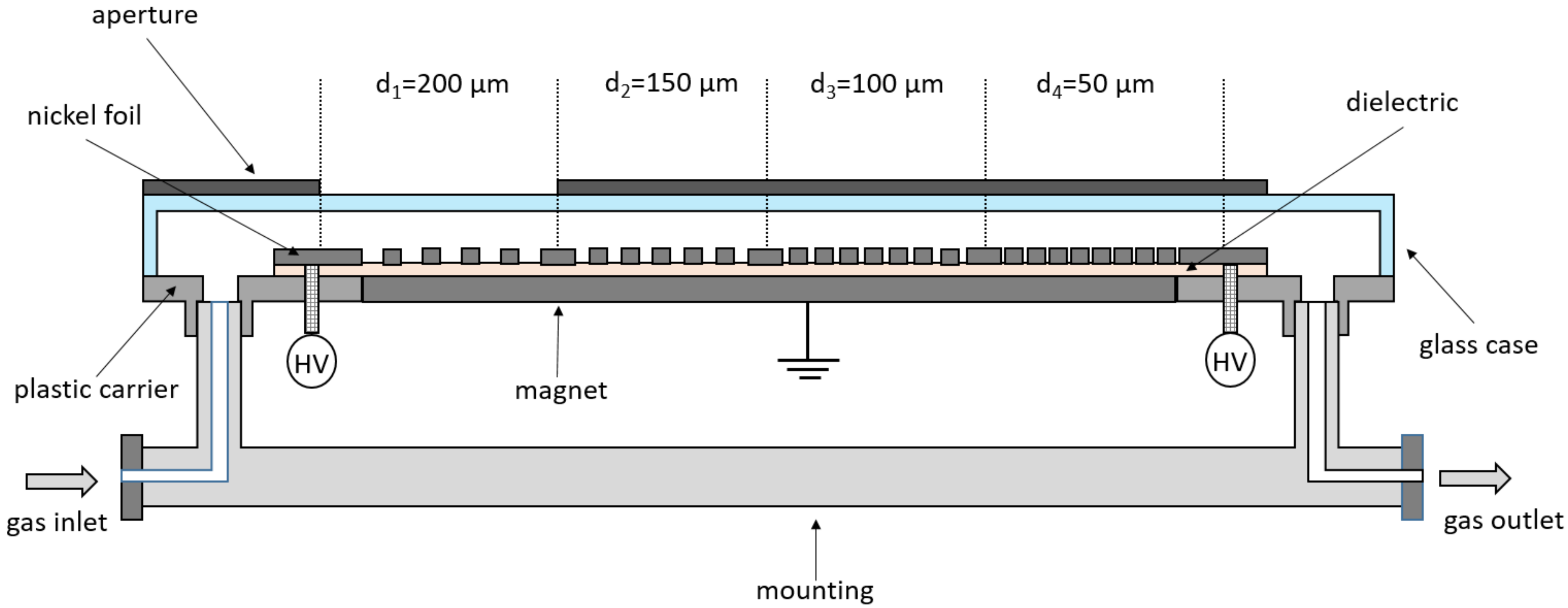


Fig.5) Sketch of a metal-grid array with exchangeable components

- This device is built like a sandwich: magnet, dielectric, metal grid
- Grid consists four different cavity structures
  →Automatic diameter variation at same condition
- Structure is enclosed with a glass case
  →Optical access and gas flow operating system
- Foil and dielectric can be changed easily

Metal-grid array device - dismountable

- Due to the magnetic holding, the device is dismountable in its components
- That allows to change the components (properties)
  →Dielectrics (glass, aluminum oxide, zirconium oxide, …)
  →Dielectric covered with a catalyst (manganese oxide,…)
  →Grid (cavity diameter and spacing, trenches, channels, …)
- After operation and treatment, components can be removed for surface investigations (LSM, XPS, …)
- How does the plasma interact with the surface or especially with the catalyst?

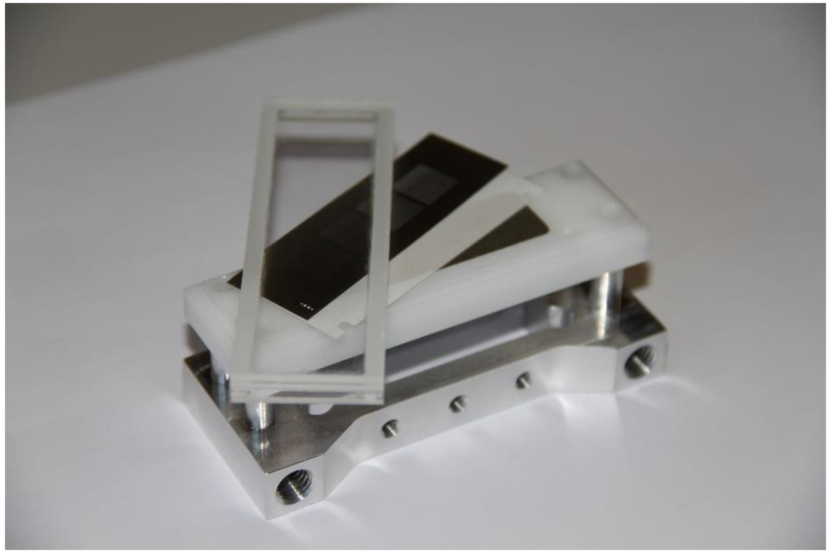


Fig.6) Photograph of the disassembled device

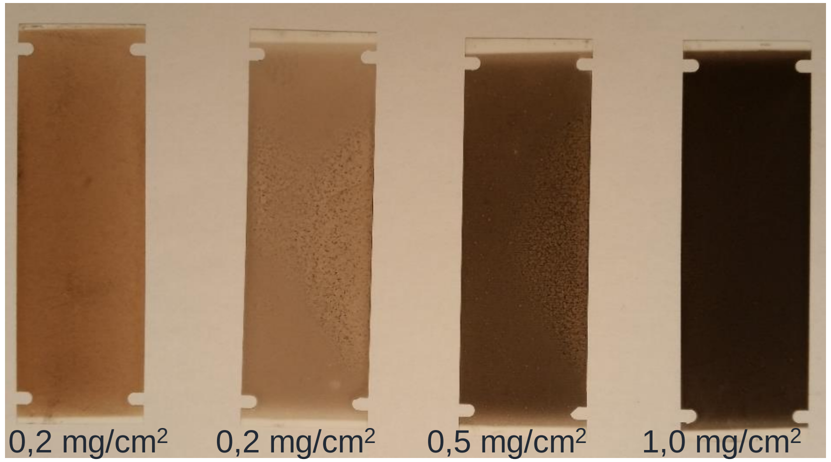


Fig.7) Dielectric covered with catalyst

Investigation of the used dielectric

- Dielectric can be investigated after operation
- Here: XPS and microscope recordings
- Black colored and cavity shaped pattern is covered on the dielectric
- XPS: Black structure consists of nickel from the grid

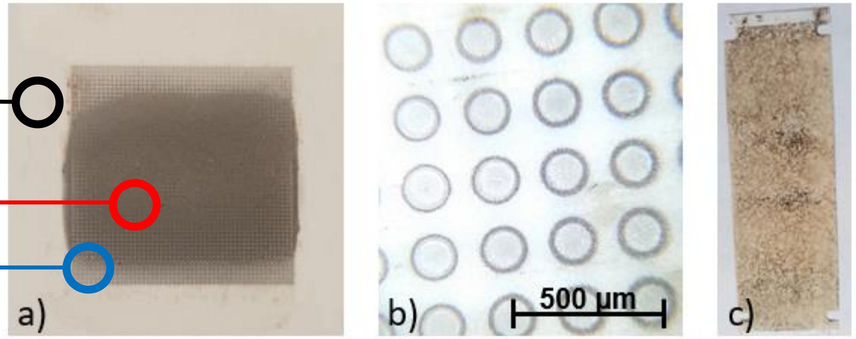


Fig.8) Photograph and microscope recording of a used and covered dielectric [3]

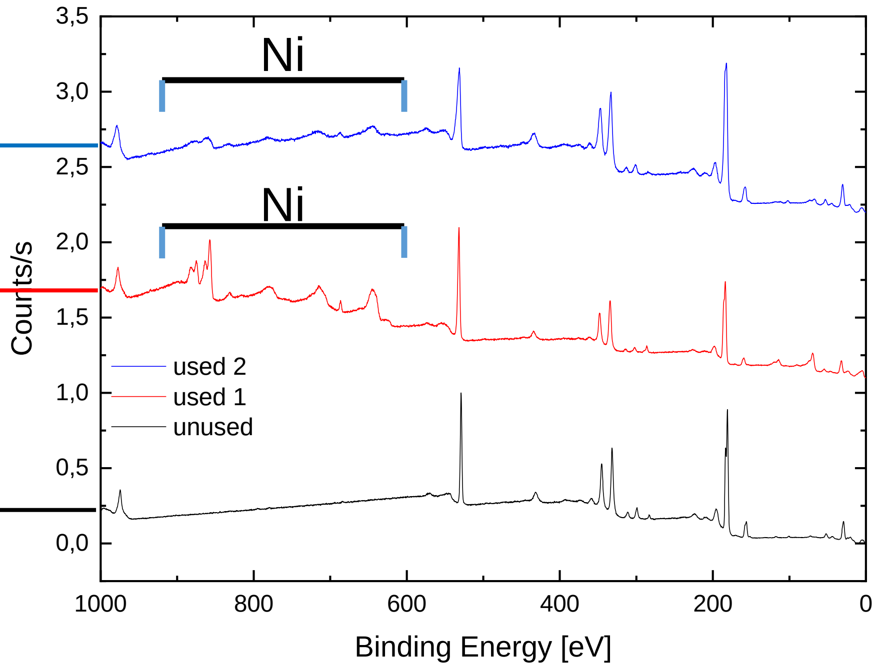


Fig.9) XPS spectra of an used dielectric after operation

[3] Sebastian Dzikowski et al. PSST 29 035028 (2020)

Metal-grid array device - Comparability

- Metal-grid and silicon-based array differ in setup and structure

  →Can they be compared with each other?

- UI-characteristic and photomultiplier signal were detected for both devices

- A voltage increase leads to several pulses

- Each pulse represent an ionization wave that travels along the array surface

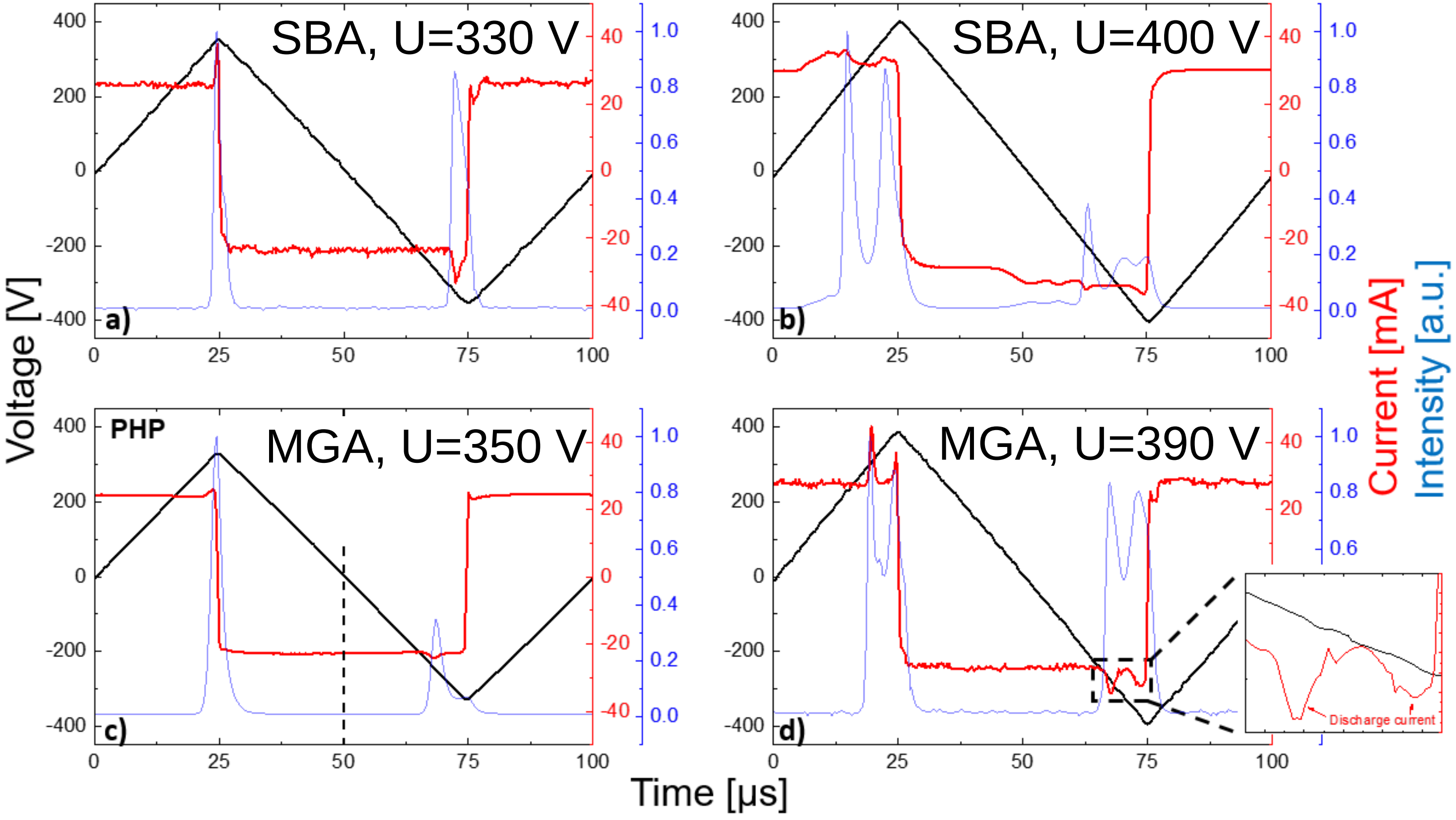


Fig.10) UI-characteristic and photomultiplier signal of a metal-grid and silicon-based array [3]

[3] Sebastian Dzikowski et al. PSST 29 035028 (2020)

Metal-grid array device – Wave character

- Phase-resolved imaging with an ICCD-camera within emission pulse

  → Time resolution of 200 ns

- Not all cavities operate at the same time

  → An ionization wave travels from bottom left to top right

  → v=10 km/s

  → Wave occurs independent of the polarity of applied voltage

- Metal-grid und silicon-based devices show this behavior

  → Can be compared

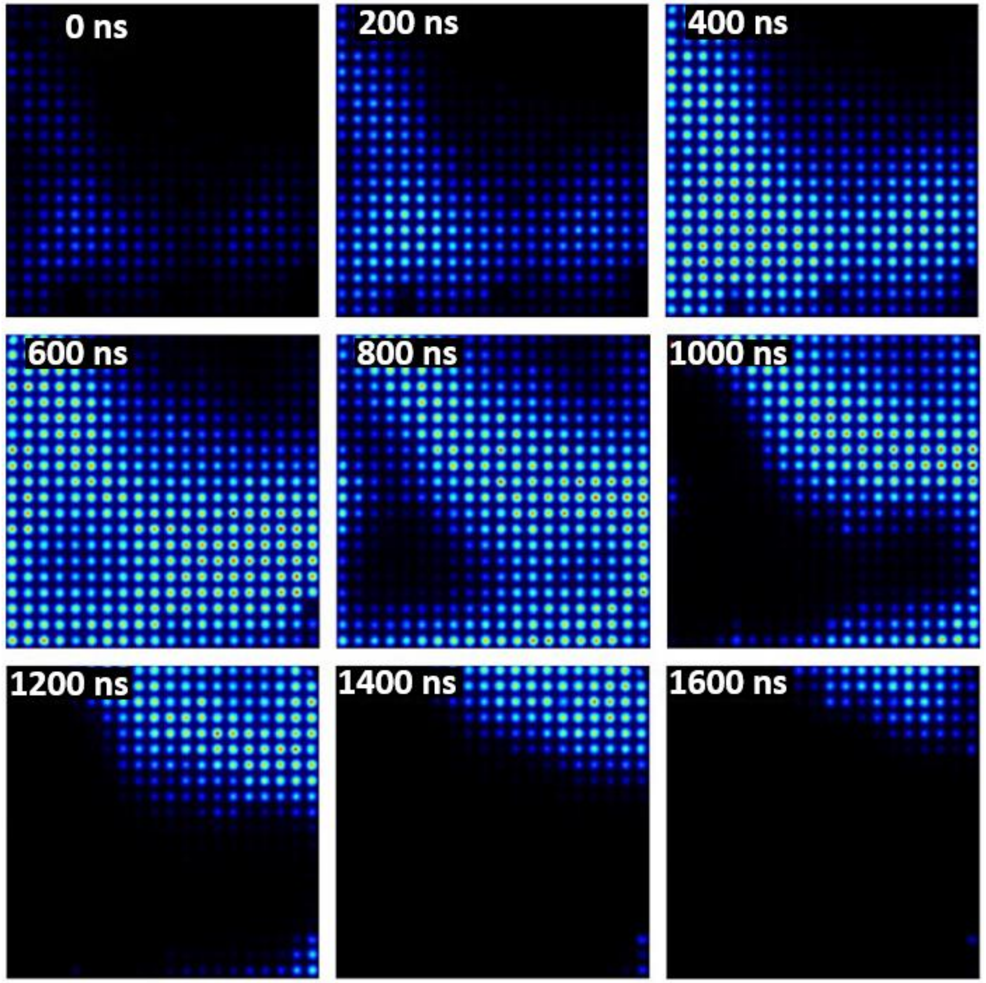


Fig.11) Phase resolved images of an ionization wave traveling along the array's surface [3]

[3] Sebastian Dzikowski et al. PSST 29 035028 (2020)

Metal-grid array device – Asymmetric discharge

- Discharge shows an asymmetric behavior for positive and negative applied voltages
- IPP: Discharge prevails at the edges outside the cavities
  →Electrons are accelerated outside
  →Ring structure
- DPP: Discharge takes place rather centered inside the cavity
  →Electrons are accelerated to the dielectric
  →Dot structure
- Observable again for both devices

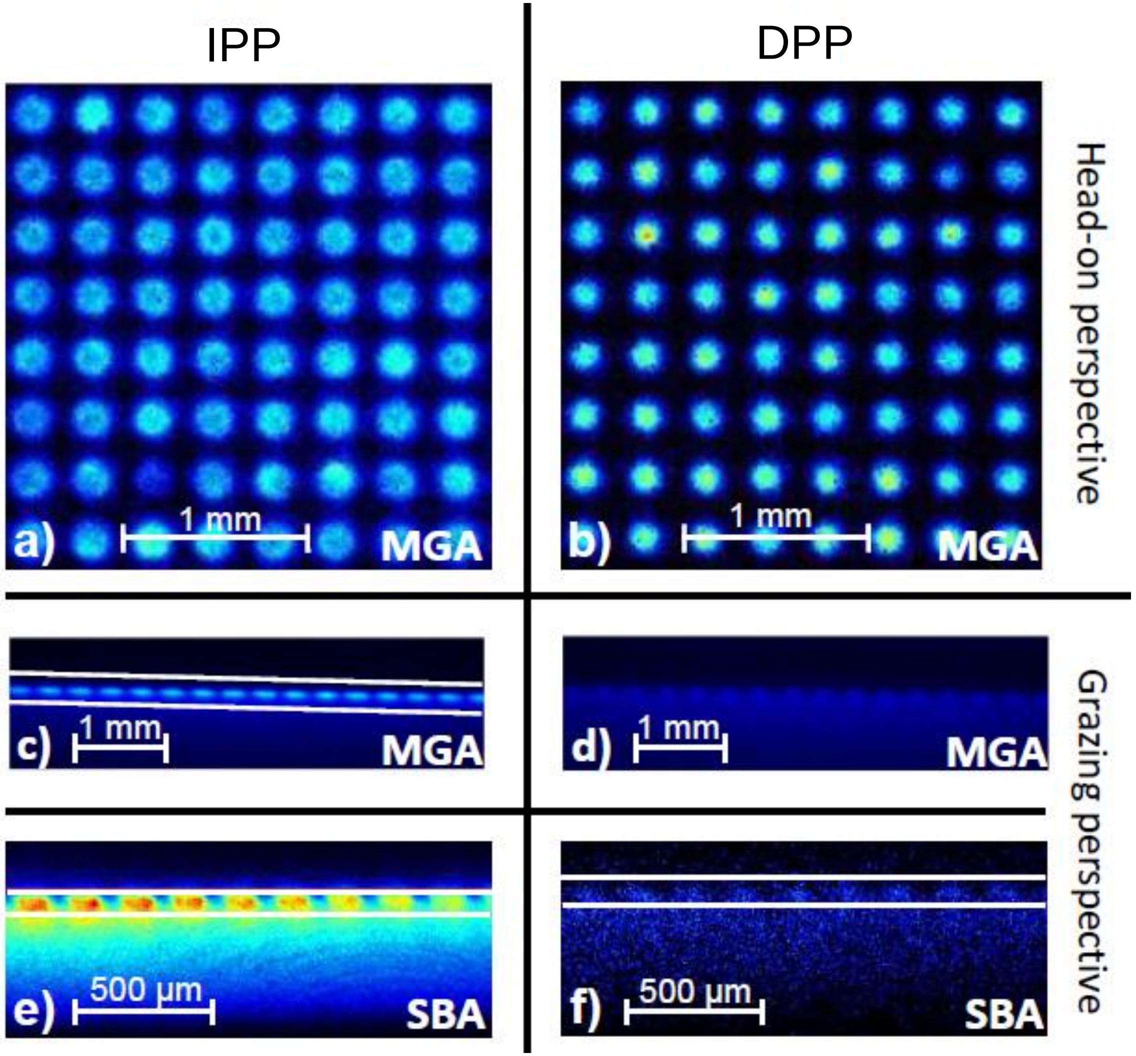


Fig.12) Asymmetric discharge behavior of a metal-grid and silicon-based array [3]

[3] Sebastian Dzikowski et al. PSST 29 035028 (2020)

Motivation – Electric field

- DBD with a pore in one dielectric was simulated [1]
- High densities and electric field are inside the pore
  - → Great conditions for catalysis
  - → Charged particles can be controlled

- Strong dependency on pore diameter and applied voltage
  - →Both parameter can be changed and controlled in a micro cavity plasma array

- Electric field strengths were never measured before on an array

- How to measure?

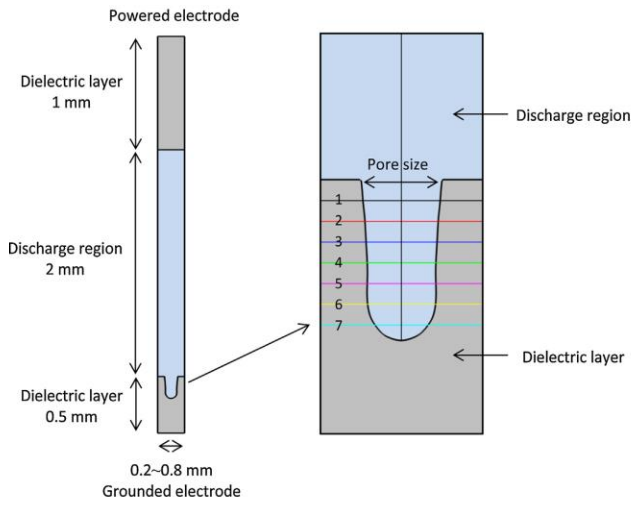


Fig.13) Sketch of the used DBD in simulation [4]

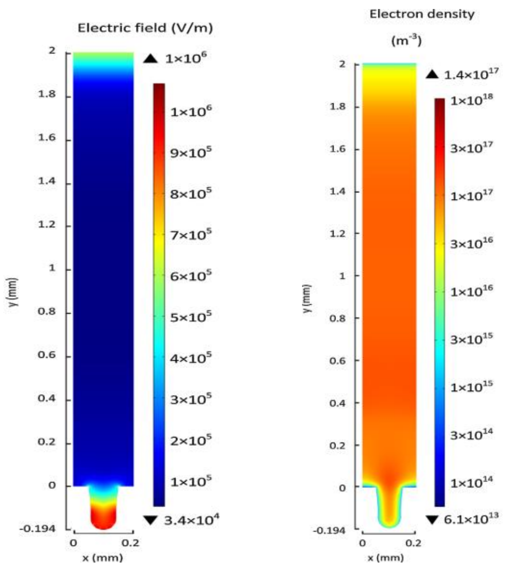


Fig.14) Electric field and electron density in the simulated DBD [4]

[4] Yu-Ru Zhang et al. Applied Catalysis B: Environmental 185 (2016)

Electric field – How to measure

- A lot of optical methods are available for measuring the electric field
- BUT: Not every method is applicable to arrays

- Laser based methods

  →No optical access to the inside of the cavities (strong field strength)

- Nitrogen based methods

  →Relative intensities of the second positive and first negative band of nitrogen

  →Admixture influence discharge

  →Further plasma parameters (EEDF, …) are necessary and unknown for the arrays

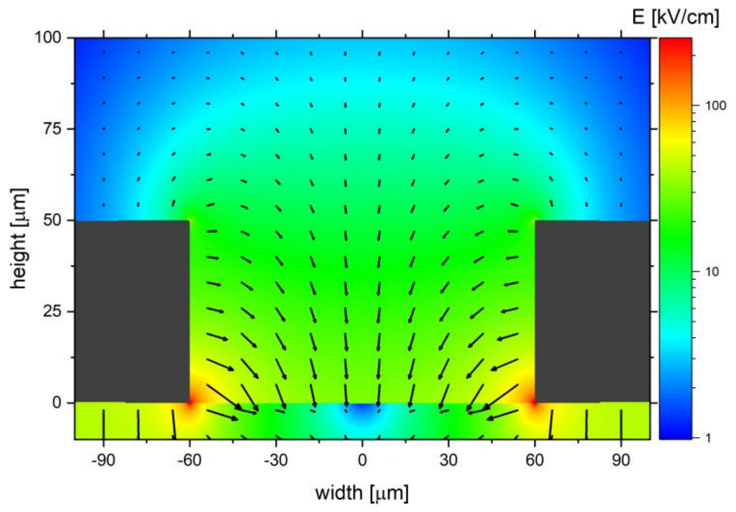


Fig.15) Applied electric field inside the cavity [5]

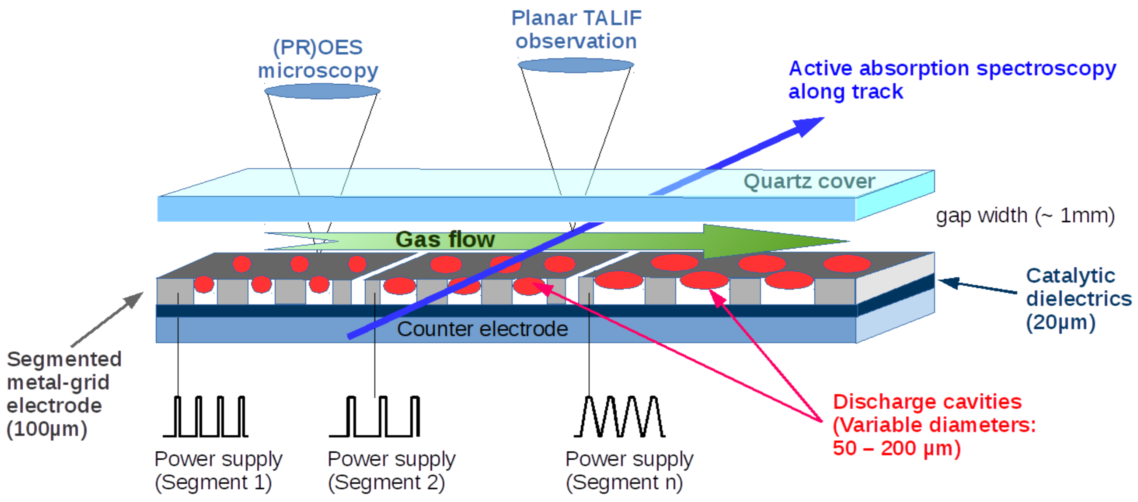


Fig.16) Optical diagnostic tools on a MCPA

[5] Simon Kreuznacht, PSST, submitted

Electric field – Stark effect

- Strong electric field → Stark splitting of atomic lines
- Here: He 492,19 nm line
- Advantage: Method is based on quantum mechanical, no further plasma parameters

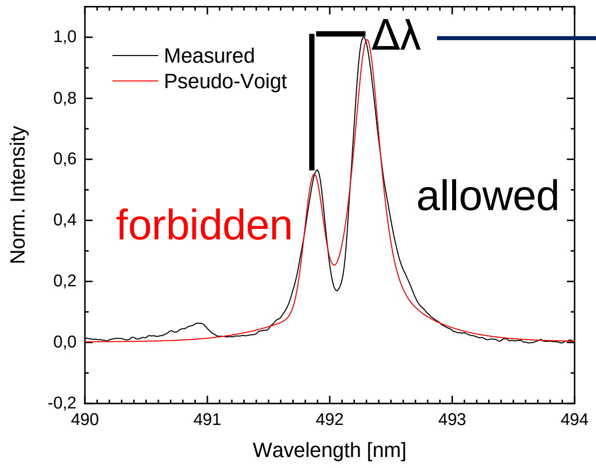


Fig.17) Recorded spectra of the split 492 nm line

- Line split in a forbidden and in an allowed part

  →High Δλ ←→ high electric field

  →Unshifted 492,19 nm line is also included

- Each part contains transitions depending on the change of the quantum magnetic number

  →Δm=0, linear polarized parallel to E-field (π-called)

  →Δm=+-1, circular polarized in E-field direction (σ-called)

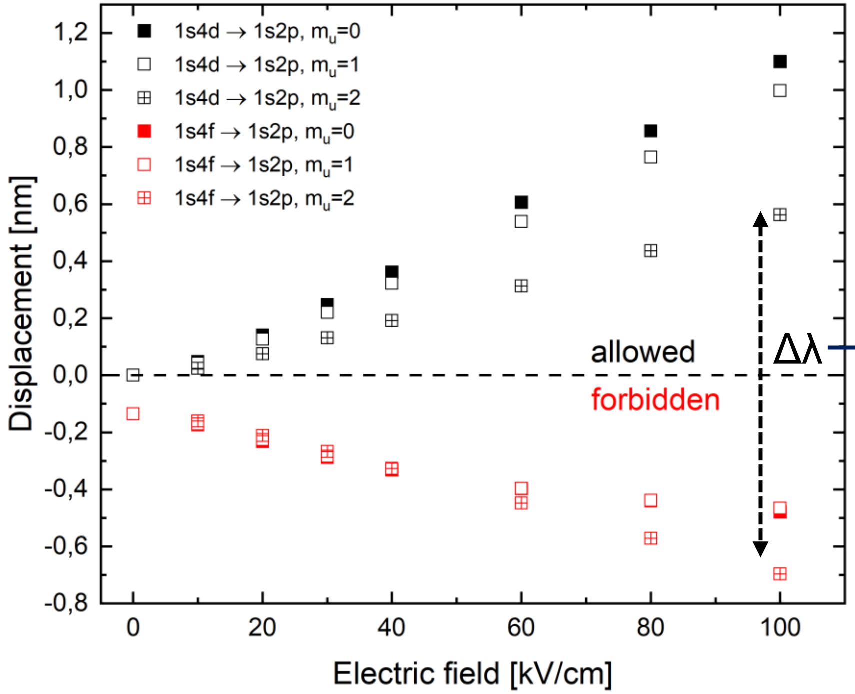


Fig.18) Profiles displacement depending on the electric field [6]

[6] J. S. Foster et al. Proc. R. Soc. Lond. Ser. A 117 137 (1927)

Experimental setup and diagnostic

- Plane grating spectrometer (PGS) for high resolved OES
- ICCD-camera is synchronized
- PMT for temporal evolution of the emission
- Light fiber can be shifted along the cavity structures

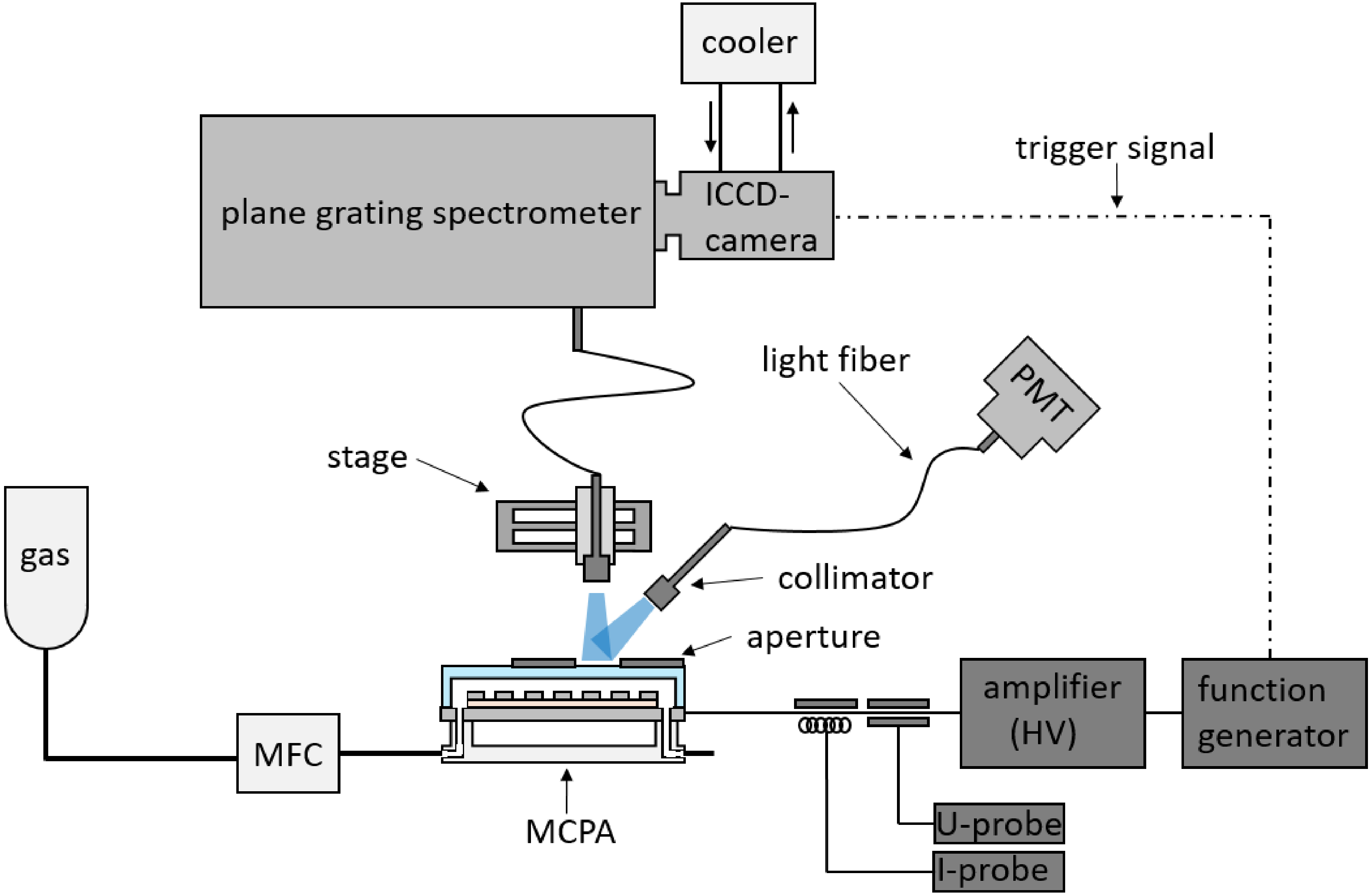


Fig.20) Sketch of the experimental setup

Electric field – Asymmetric discharge

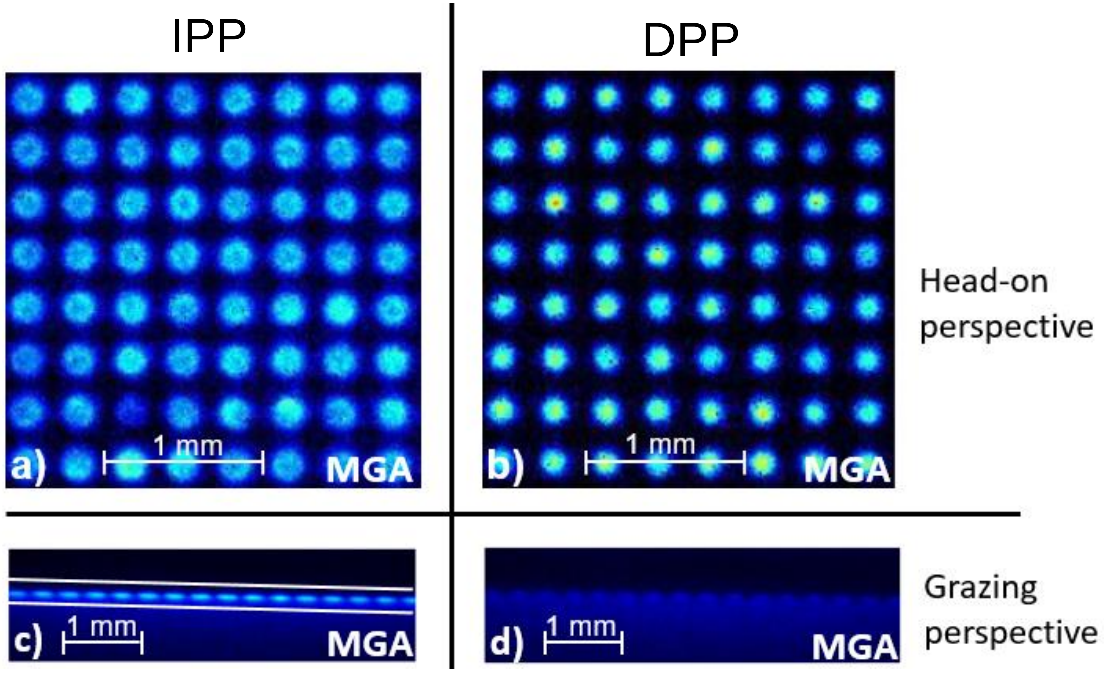


Fig.21) Phase resolved images of the asymmetric discharge

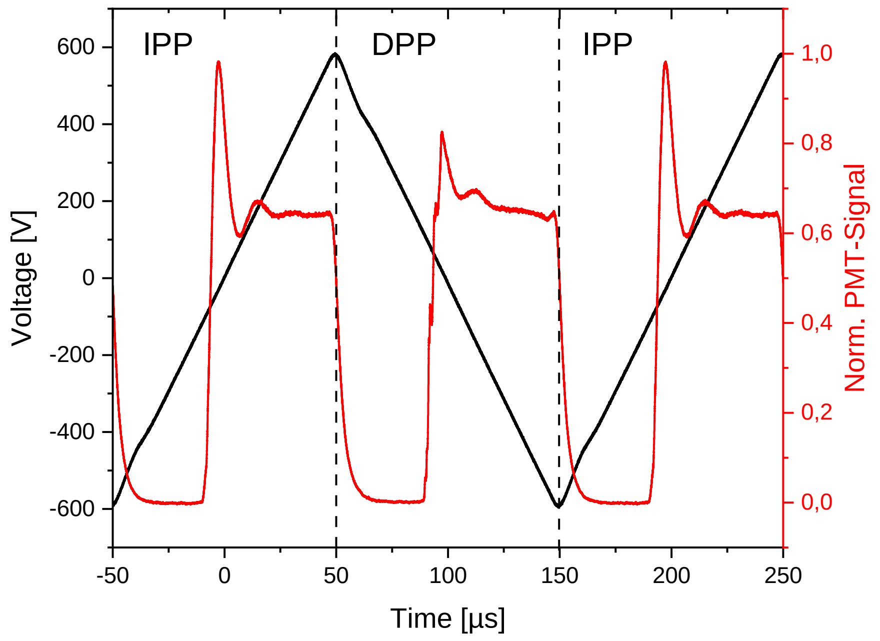


Fig.22) PMT-signal depending on the applied voltage

- Asymmetric discharge behavior in positive potential phase (IPP) and negative potential phase (DPP)

- IPP: Ring-structure outside the cavities
- DPP: Dot-structure inside the cavities

- How does the electric field differ?

  →First: Time integrated measurements for PPS and NPS

Electric field – Cavity diameter variation

- All four cavity structures are operated under same conditions

- 700 V
- 15 kHz
- 2 slm

- π and σ : Same trend, but values different

- Small intensity for the 50 µm cavities

- IPP: Nearly constant
- DPP: Decreasing with increasing diameter

- Strongest electric field at edges inside the cavity ←→ discharge inside the cavity during DPP

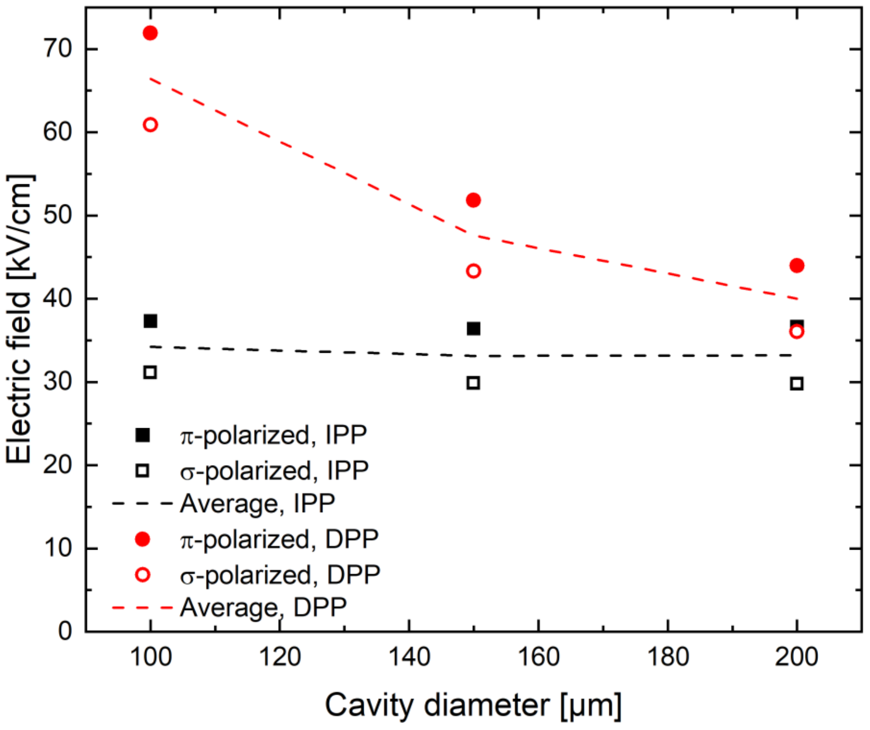


Fig.23) Measured electric field depending on the cavity diameter

Electric field – Applied voltage variation

- Applied voltage variation on 200 µm and 10 µm cavities

- 15 kHz
- 2 slm

- IPP: Constant trend for both cases
- NPS: Higher electric field again and decreasing trend

- Why does the electric field decrease or keep constant with higher applied voltage?

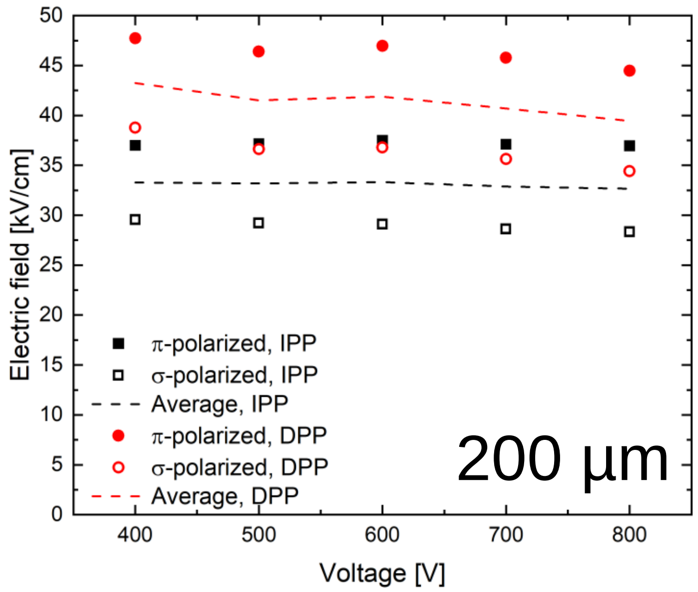


Fig.24) Measured electric field depending on the applied voltage

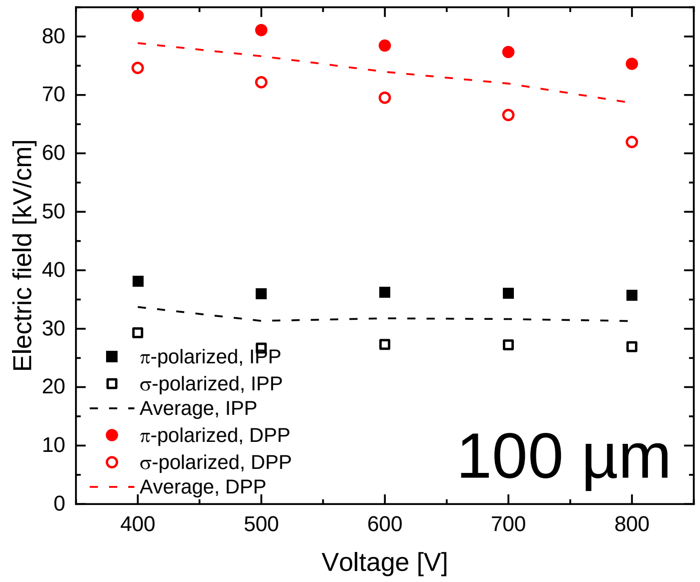


Fig.25) Measured electric field depending on the applied voltage

Electric field – Time resolved measurements

- Time resolved measurements on 200 µm cavities
  →Highest intensity
- 15 kHz
- 2 slm
- 700 V
- First case: Time resolution of 1 µs
  →IPP: Rather constant trend, not clear
  →DPP: Electric field decrease within the slope
- Second case: Time resolution of 500 ns
  →Values are reproduceable
  →Electric field behaves like the emission

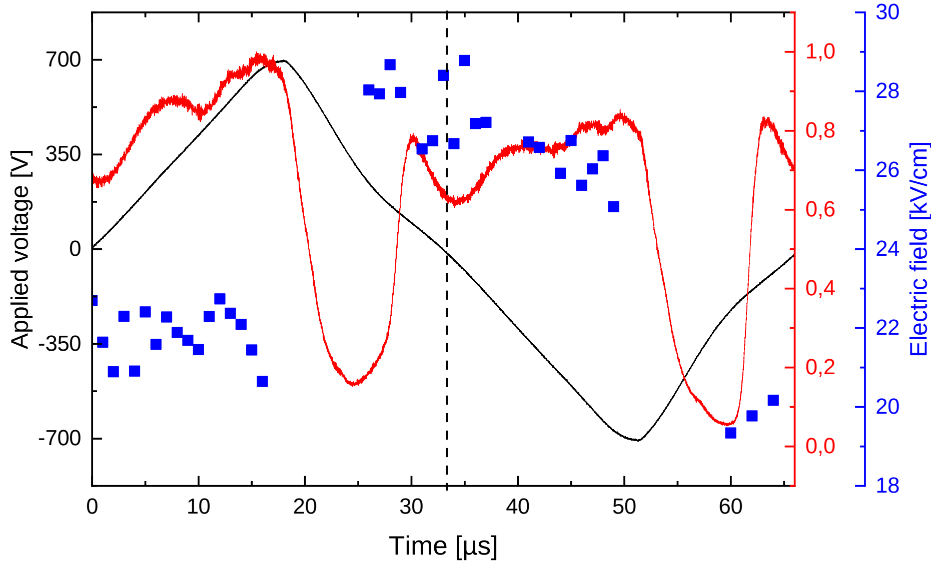


Fig.26) Time-resolved electric field strengths (1 µs)

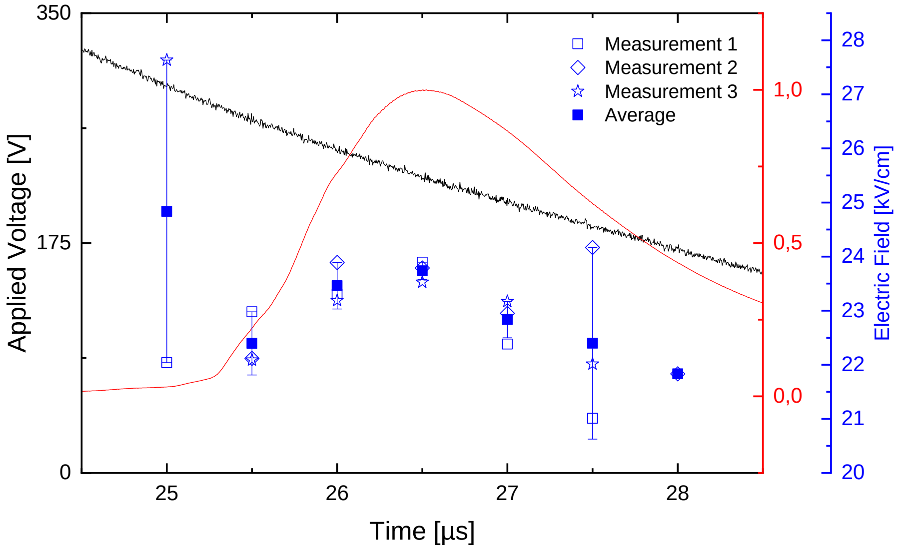


Fig.27) Time-resolved electric field strengths (500 ns)

Electric field – Success and challenges

- Success
  →Stark effect can be applied
  →Field strengths are in a reasonable range
  →Comparable to some models
  →Values and trends are reproducible
  →Time resolved measurements possible

- Challenges
  →Fight with low intensity
  →Measurements are spatial-integrated
  →Emission dependent diagnostic

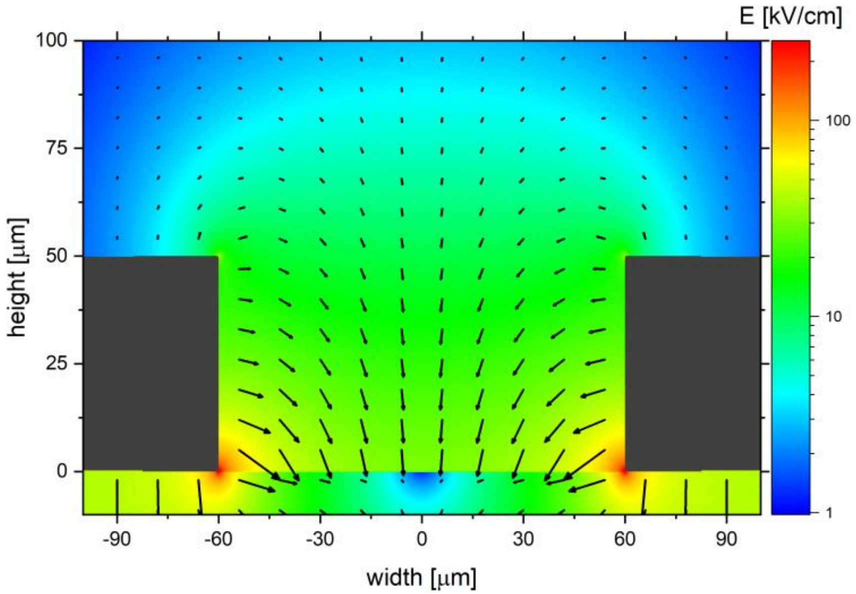


Fig.28) Applied electric field inside the cavity [5]

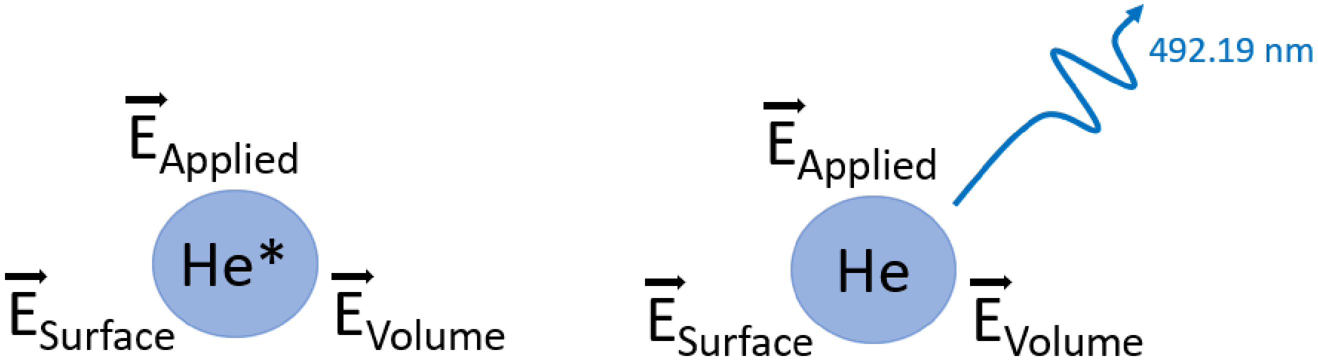


Fig.29) Sketch Stark effect

Radial discharge distribution – Cavity variation

- Spatial resolved measurements are not possible
- Camera and different filter are connected ahead the MCPA
- → radial discharge distribution

- Cavity diameter variation
- Same conditions as in the electric field measurement

- IPP: Stronger emission at the edges for 200 and 150 µm
- Larger diameter ←→ discharge tends to prevails outside
- DPP: No modulation, rather a plateau for large diameters

- Results correspond to the asymmetric discharge behavior

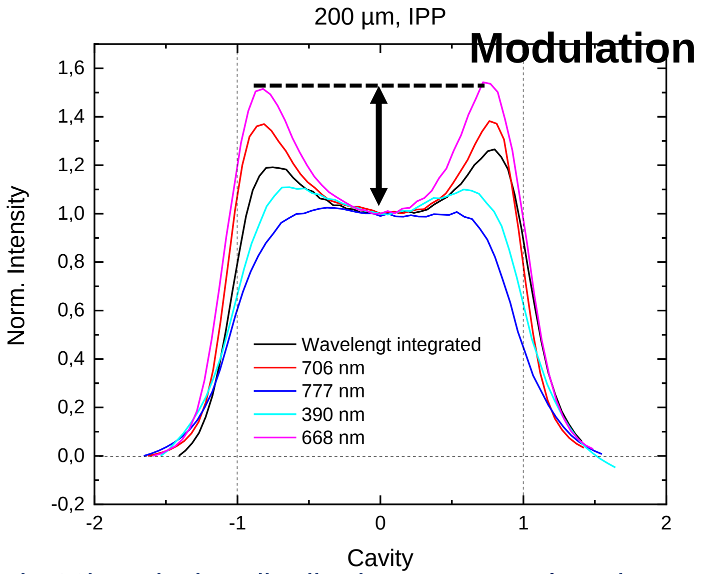


Fig.30) Emission distribution IPP, wavelength resolved

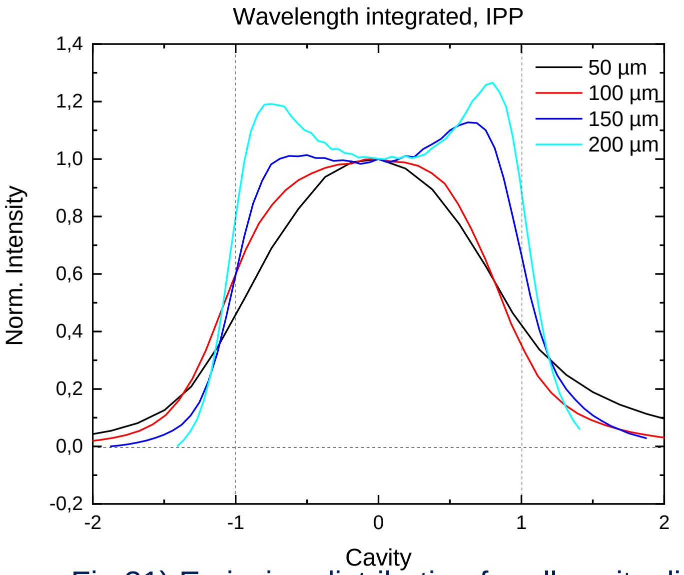


Fig.31) Emission distribution for all cavity diameter

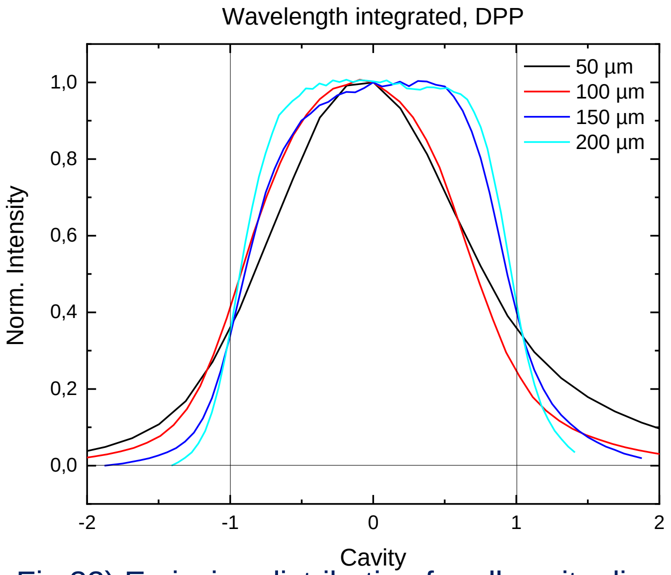


Fig.32) Emission distribution for all cavity diameter

Radial discharge distribution – Voltage variation

- 200 µm cavities
- IPP: Modulation decreases with higher voltage
- → The cavity is filled out with the discharge
- DPP: Plateau is unchanged
- Depending on both parameters the discharge changes between the edges (high field) and center in the IPP
- How does the profile change along the cavity height?
- Generally, more changes in the IPP, but the electric field shows a change in the DPP
- In context of the electric field the results are still difficult to interpret

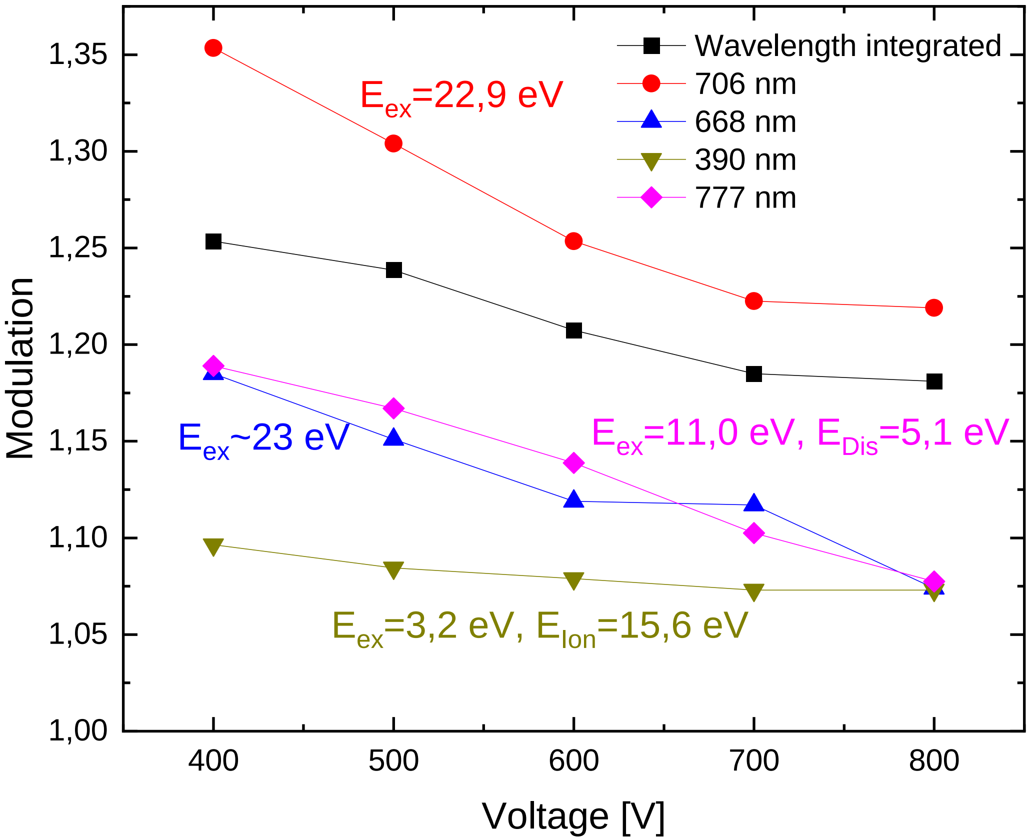


Fig.33) Modulation depending on the applied voltage

Microchannel device

- Allows an insight in the “cavity”
- Investigative “support” for the array

- d=120 µm

- For small voltage amplitudes, the discharge ignites just at the amplitude

  →No surface charges that help to ignite
- For high amplitudes the discharge ignites already in the half period before

- Same effect also detectable for the array

  →Can be compared

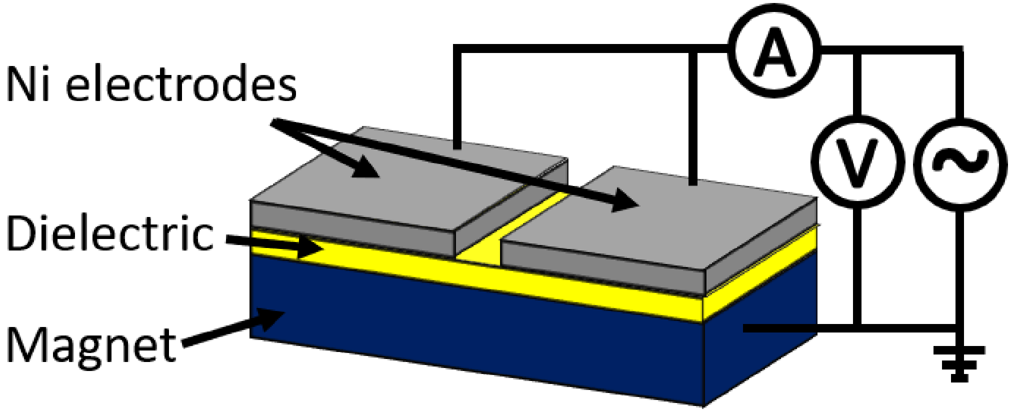


Fig.34) Sketch of the microchannel device [5]

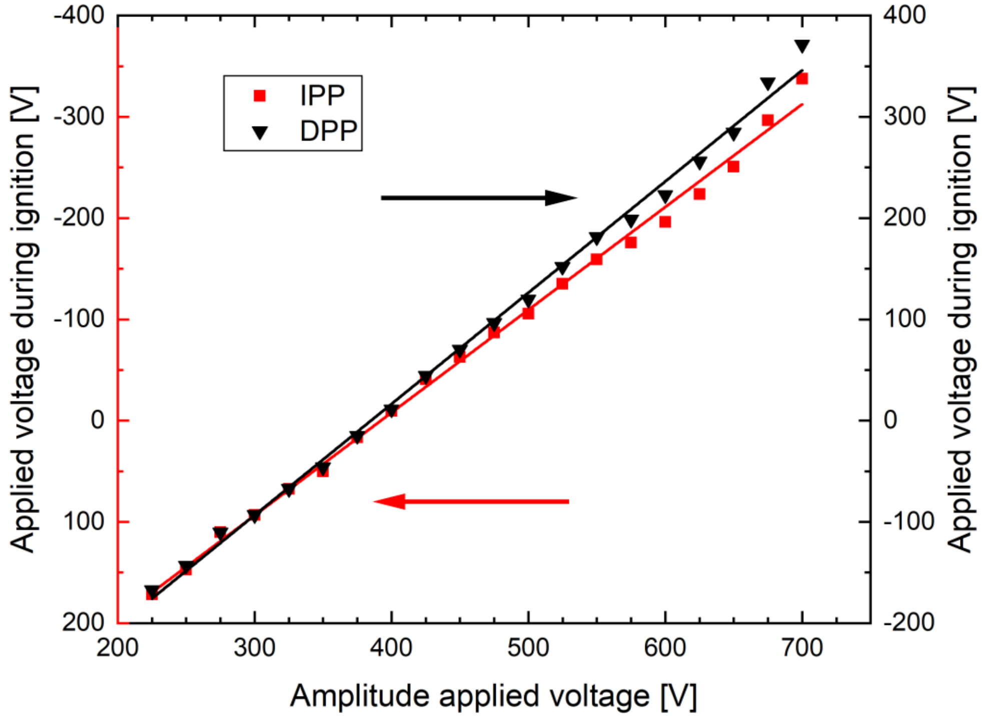


Fig.35) Ignition voltage depending on amplitude applied voltage [5]

[5] S. Kreuznacht et al. PSST, submitted

Microchannel device – side view images

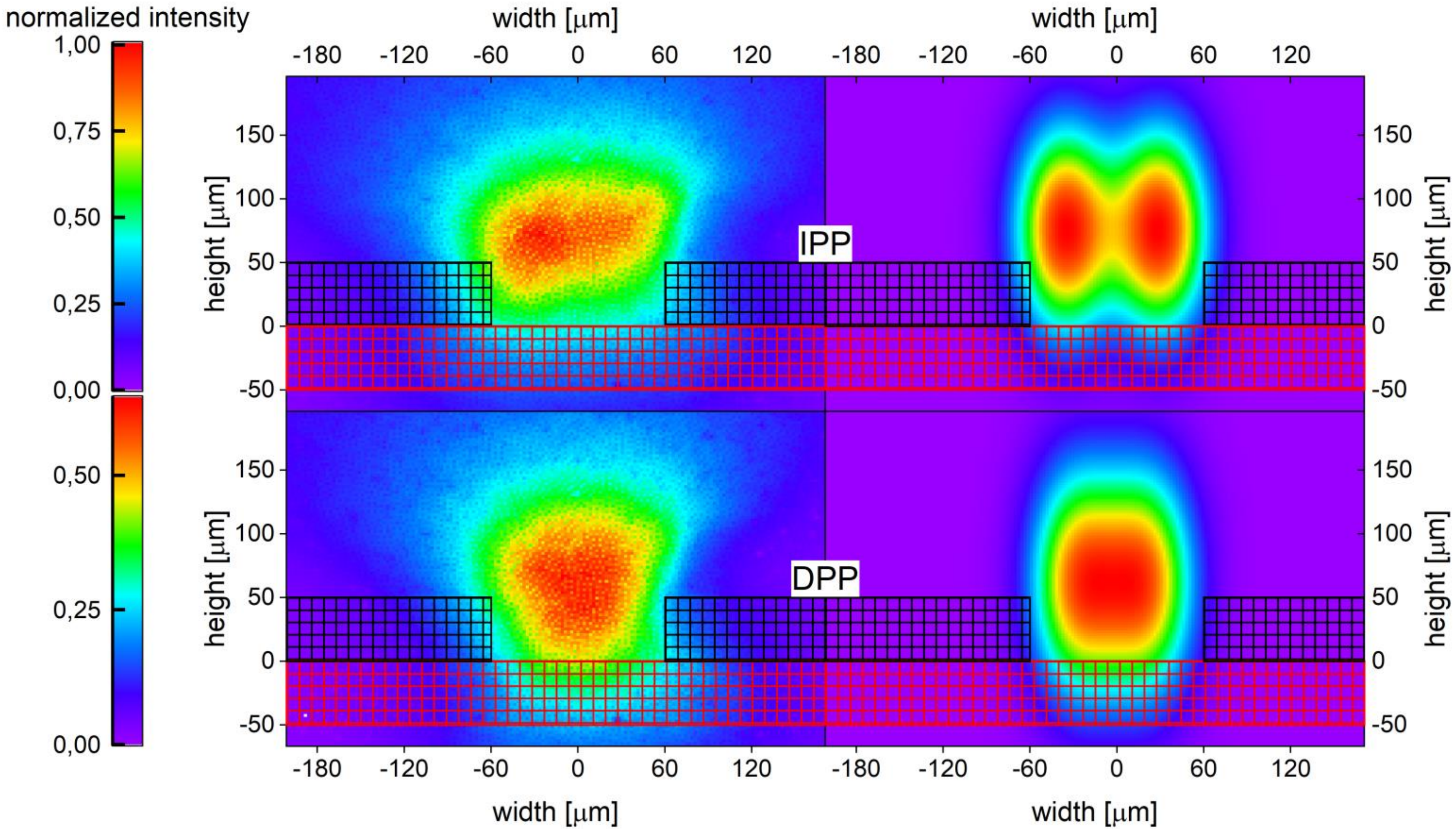


Fig.36) Phase resolved images of the discharge in a microchannel device from the side [5]

- Goal: Discharge profile in the height
- IPP: Discharge takes place at the opening of the channel
- DPP: Discharge rather centered along the height
- Asymmetric character observable
- How does the position change?

[5] S. Kreuznacht et al. PSST, submitted

Microchannel device – side view profiles

- F= 2slm
- f=15 kHz

- IPP: Position seems to be nearly constant
- DPP: Discharge center move to the dielectric (high electric field, surface charges)

- Microchannel is a first attempt as an investigative support for the array

→Gap width (cavity diameter) was not varied

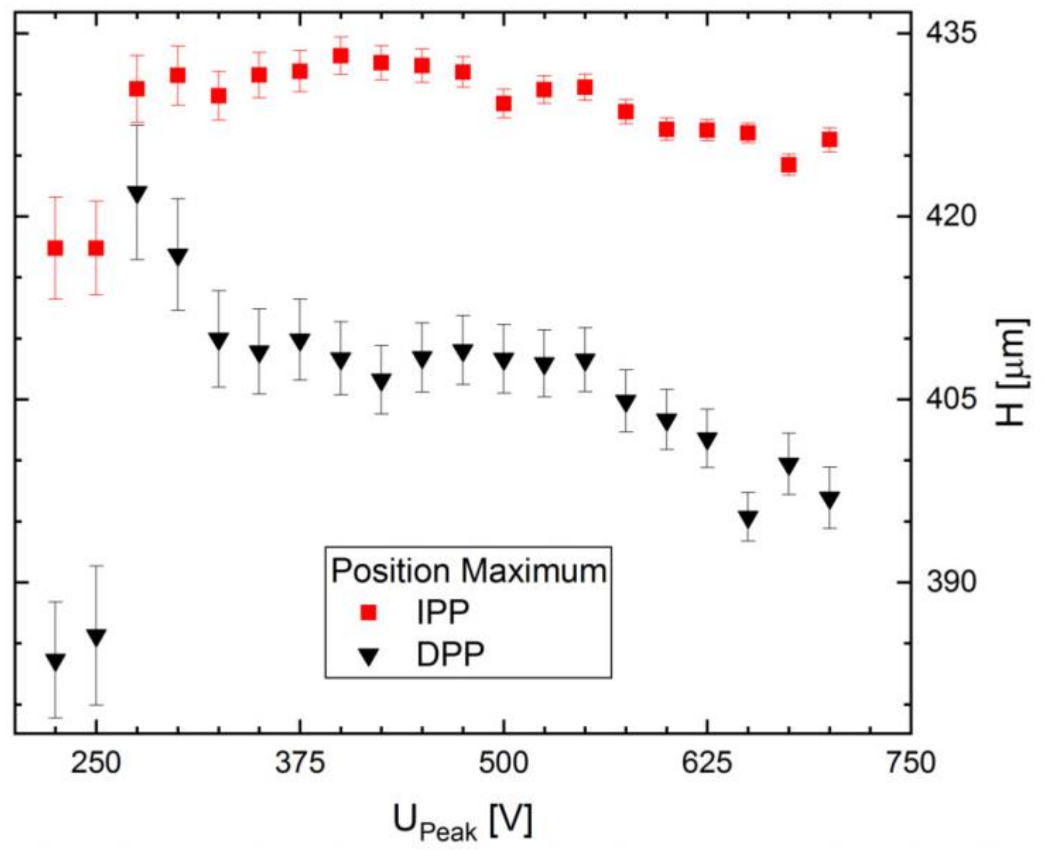


Fig.37) Discharge position in a microchannel device depending on the applied voltage

Electric field – All in all…

- Stark effect was a nice method to get electric field strengths and trends
- Challenges: We see that electric field that the excited helium particles see at the time of emission

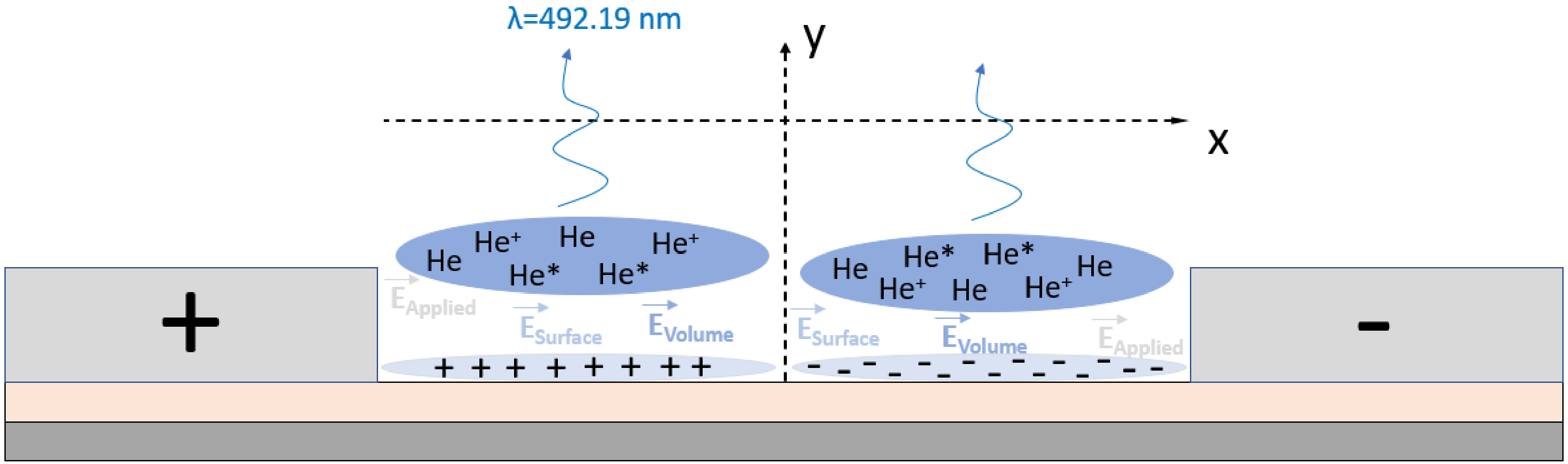
  →Trends cannot be explained yet
- The electric field is caused by

  →Surface charges on the dielectr

  →Volume charges in cavity

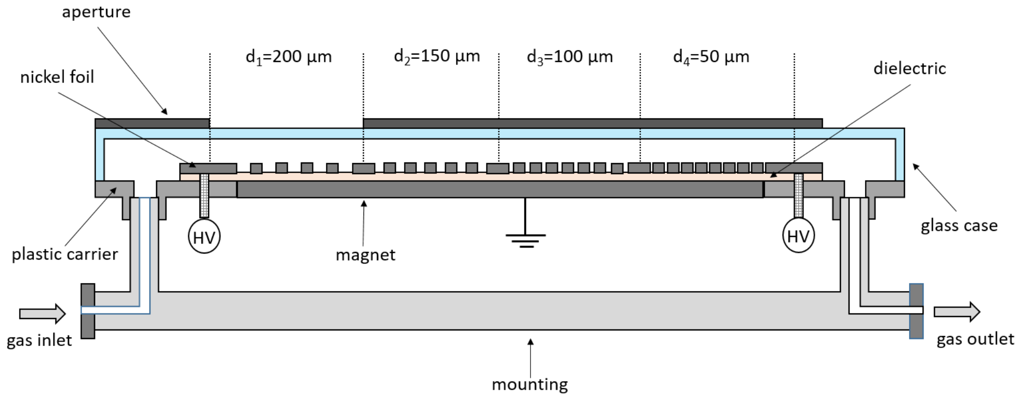
  →Nickel electrode
- All contributions depends on the cavity dimension and applied voltage
- Position and shape of the discharge also has a dependency on these parameter
- Wave character, asymmetric discharge,…
- How is everything connected?

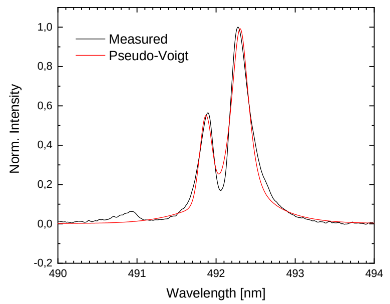
  →Research!

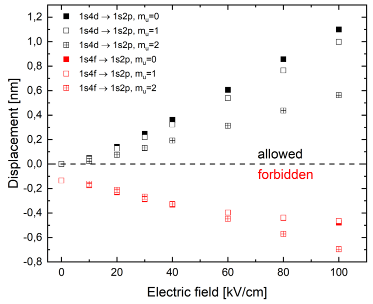


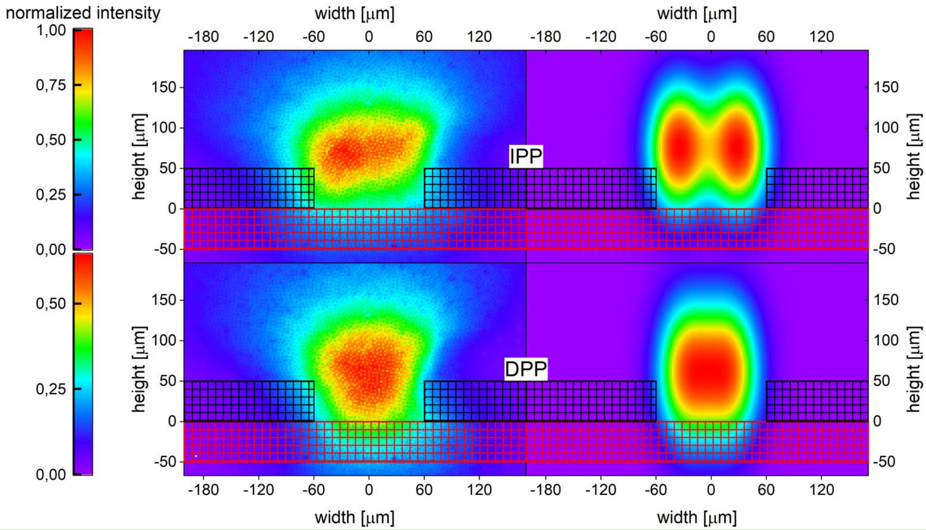
Conclusion

- Our metal-grid array is a great alternative to the silicon-based devices that…
  - →is demountable in its components
  - →has the required lifetime for long-term investigations
- The Stark effect can be applied on the MCPA and provide…
  - →reasonable values for the electric field
  - →interesting phase-dependent trends
- Optical emission spectroscopy…
  - →enables a deeper insight in the general discharge behavior
  - →is supported by the micro-channel device relating to the optical access









Collaboration and funding

This project is supported by the Deutsche Forschungsgemeinschaft in the frame of the SFB CRC 1316
Transient Atmospheric Plasmas
From Plasmas to Liquids to Solids

SFB 1316 Transient Atmospheric Plasmas
from plasmas to liquids to solids

Thank you for your attention!

Questions?

Electric field – Polarisation

- Polarizer has no influence on the spectra

- E-field parallel to surface normal: σ-polarised emission
- E-field orthogonal to surface normal: π- polarised emission

- Due to the radial symmetry, orientation of polariser has no influence

- Spectrum is fitted with 5 components
  →Unshifted 492,19 nm
  →2 π-components (forbidden and allowed)
  →2 σ -components (forbidden and allowed)

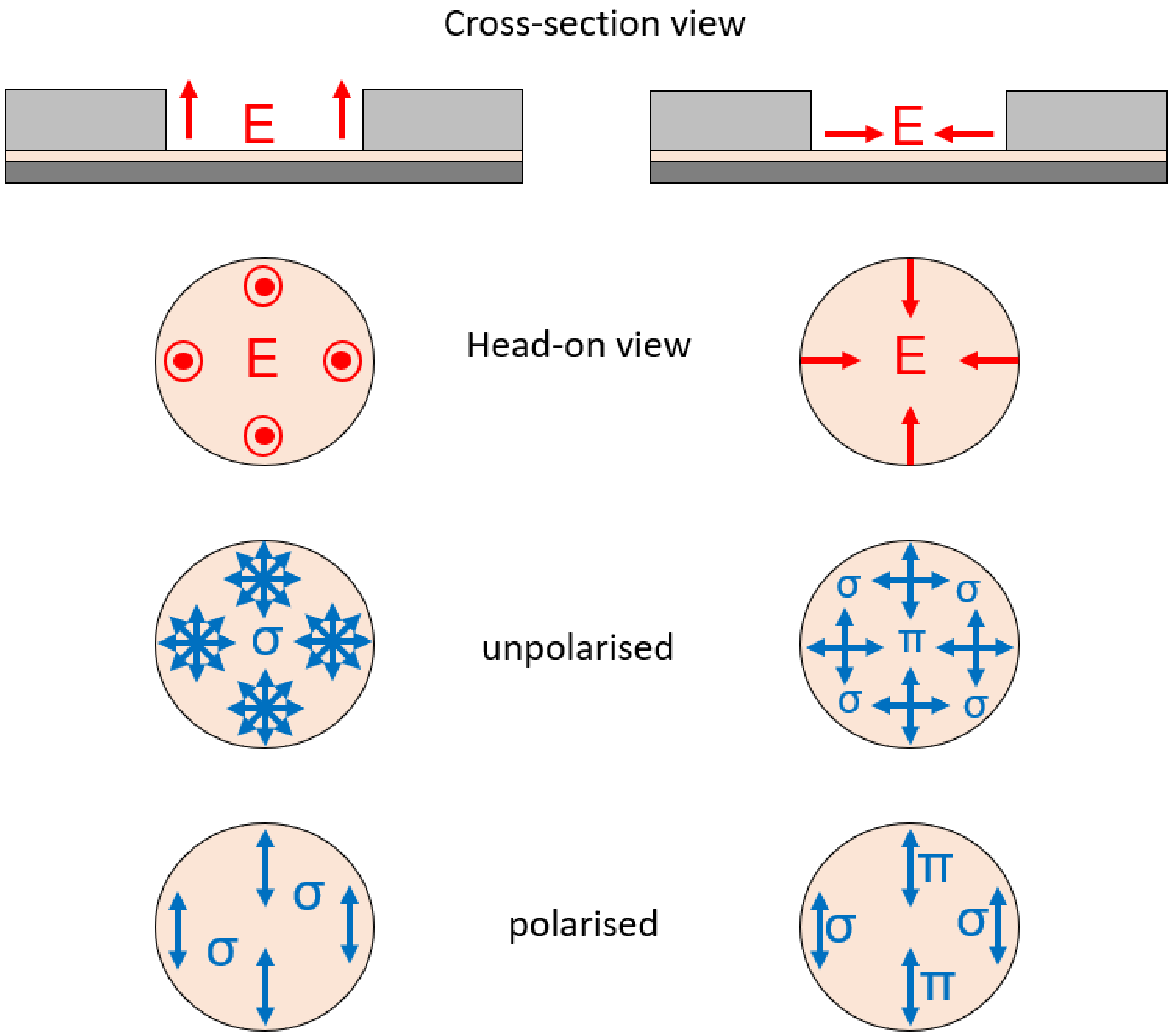


Fig.19) Sketch of the polarized emission of an array