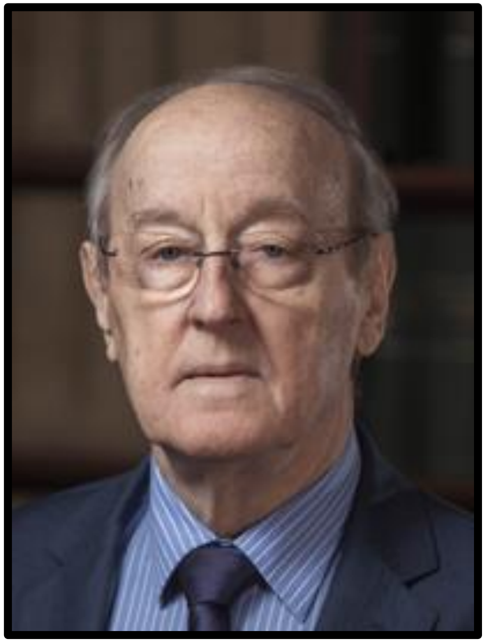
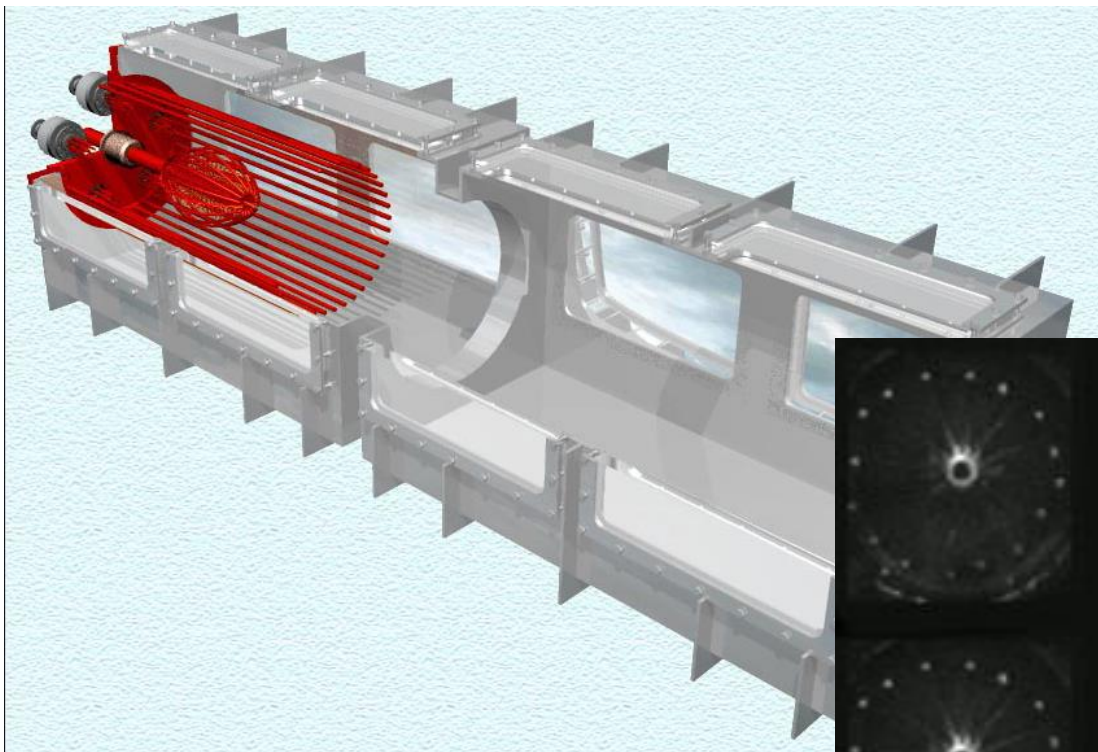
Prof. Jagoš Purić (1942-2022)

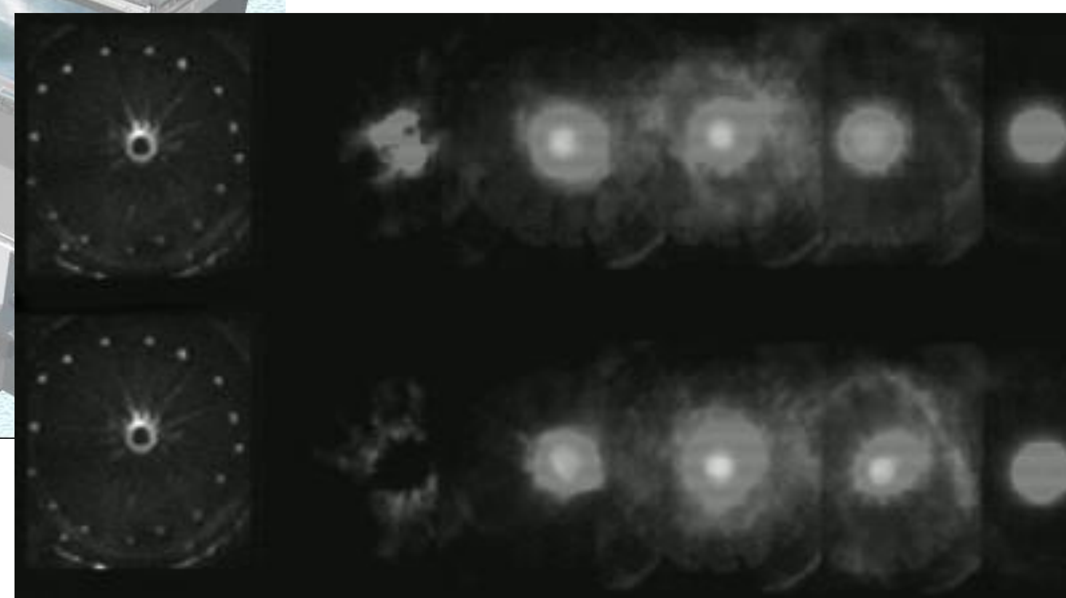


- Member of the *Belgrade school of Plasma Spectroscopy* along with N. Konjević, M. Dimitrijević, J. Labat and M. Platiša.
- Most notable publications concern experimental Stark broadening of Ne, Ar, alkaline elements etc.
- Established the method of Regularities of the Stark broadening and shift parameters of spectral lines in plasma (1985).
- Longtime member of scientific committees of ICPIG and ESCAMPIG.
- Host of ICPIG 1989 in Belgrade.
- Collaborator of Culham JET plasma facility in its pioneering days (1973)
- Collaborations with *Meudon Observatory, Universities of Osaka and Nagoya, Minsk Academy of Sciences etc.*
- Rector of the University of Belgrade 1998-2000.

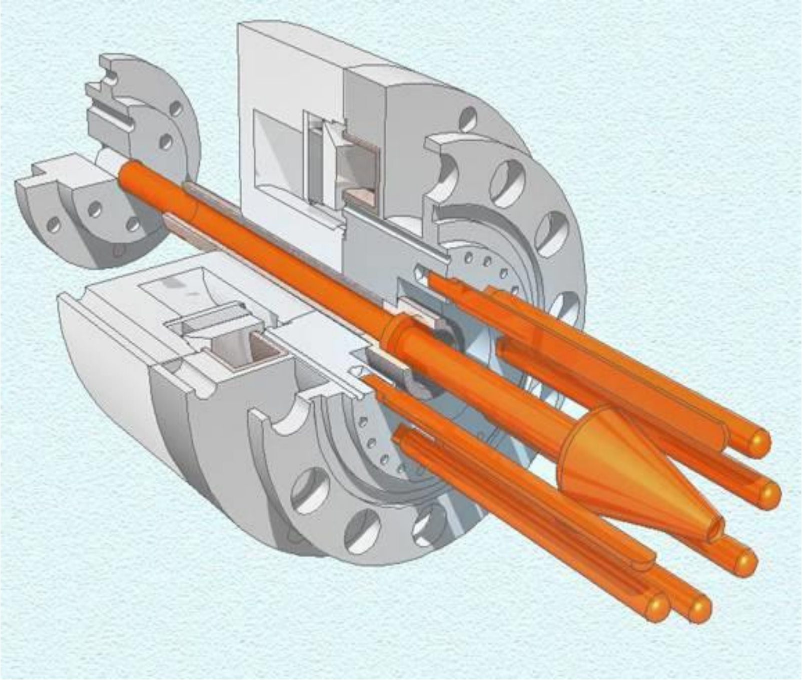
Standing: Srdjan Samurovic, Luka Ch. Popovic, Mira Terzic, Bozidar Vujicic, Petar Grujic, Ljiljana Dobrosavljevic, Sonja Jovicevic, Stevica Djurovic, Gillian Peach, Nikola Konjevic, Vladimir Milosavljevic, Mihajlo Platisa, Milivoje Cuk, Milan S. Dimitrijevic, Jagos Puric, Jaroslav Labat, Alexander P. Voitovich and M. Pavlov.
In front: Branislav Blagojevic, Gojko Djurasevic, H. G. Escobar, Milivoje Ivkovic, Leonid Ya. Min'ko, Ljubinko Ignjatovic, Zoran Mija-tovic and Radomir Kobilarov.

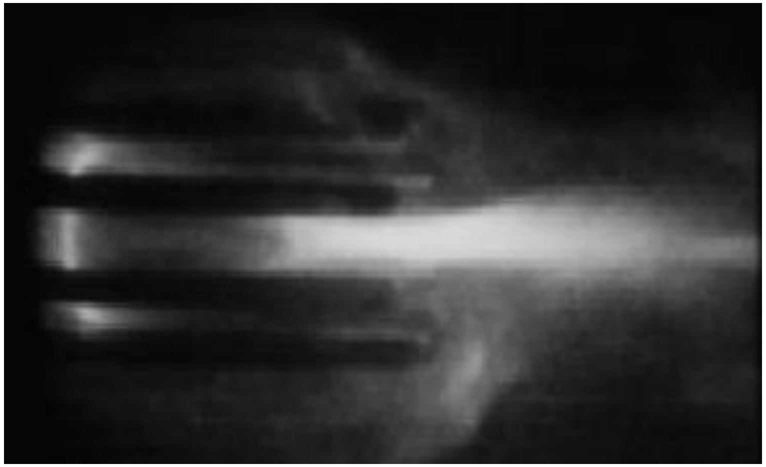
- Laboratory for Plasma Physics
- New plasma sources for high energy plasma and environmental application
- Spectral line shapes with features applicable to astrophysical and fusion plasma
- Further work on Stark regularities, even including machine learning

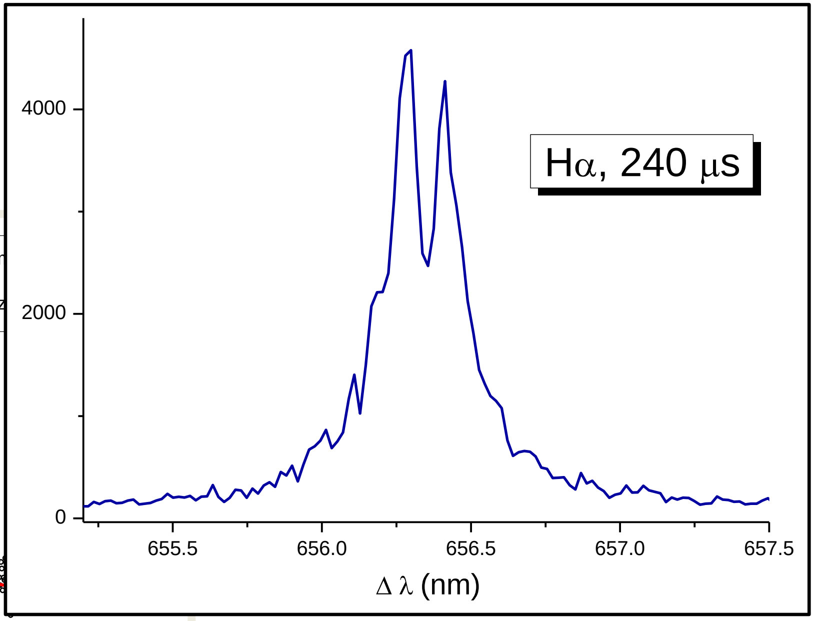


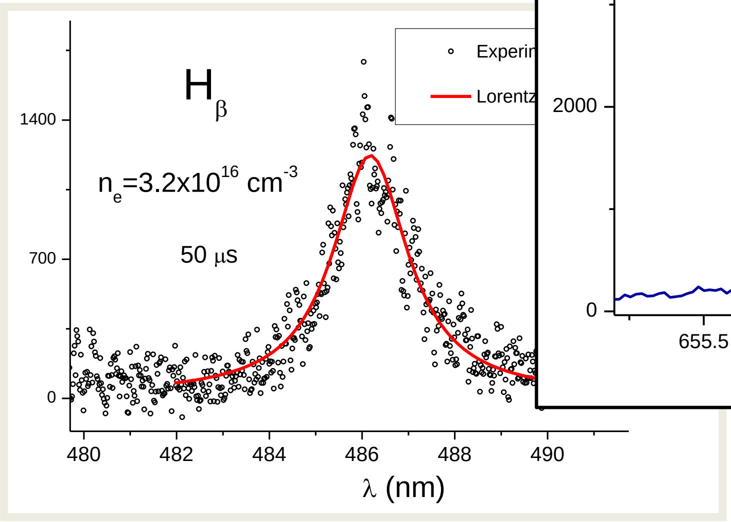


MPC- Compression plasma flow



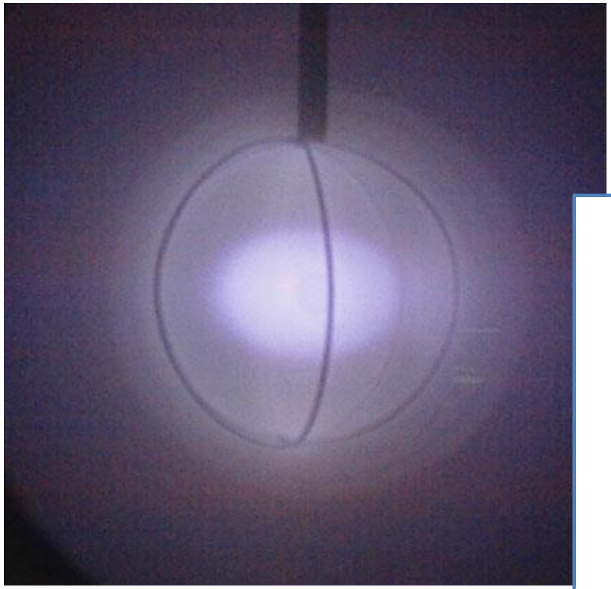


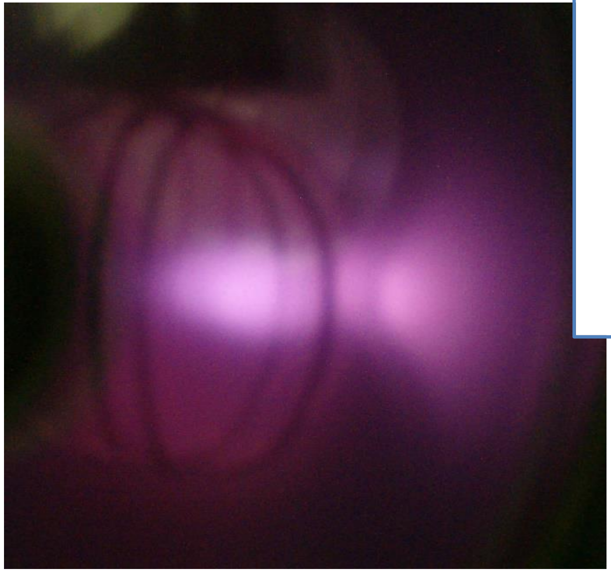


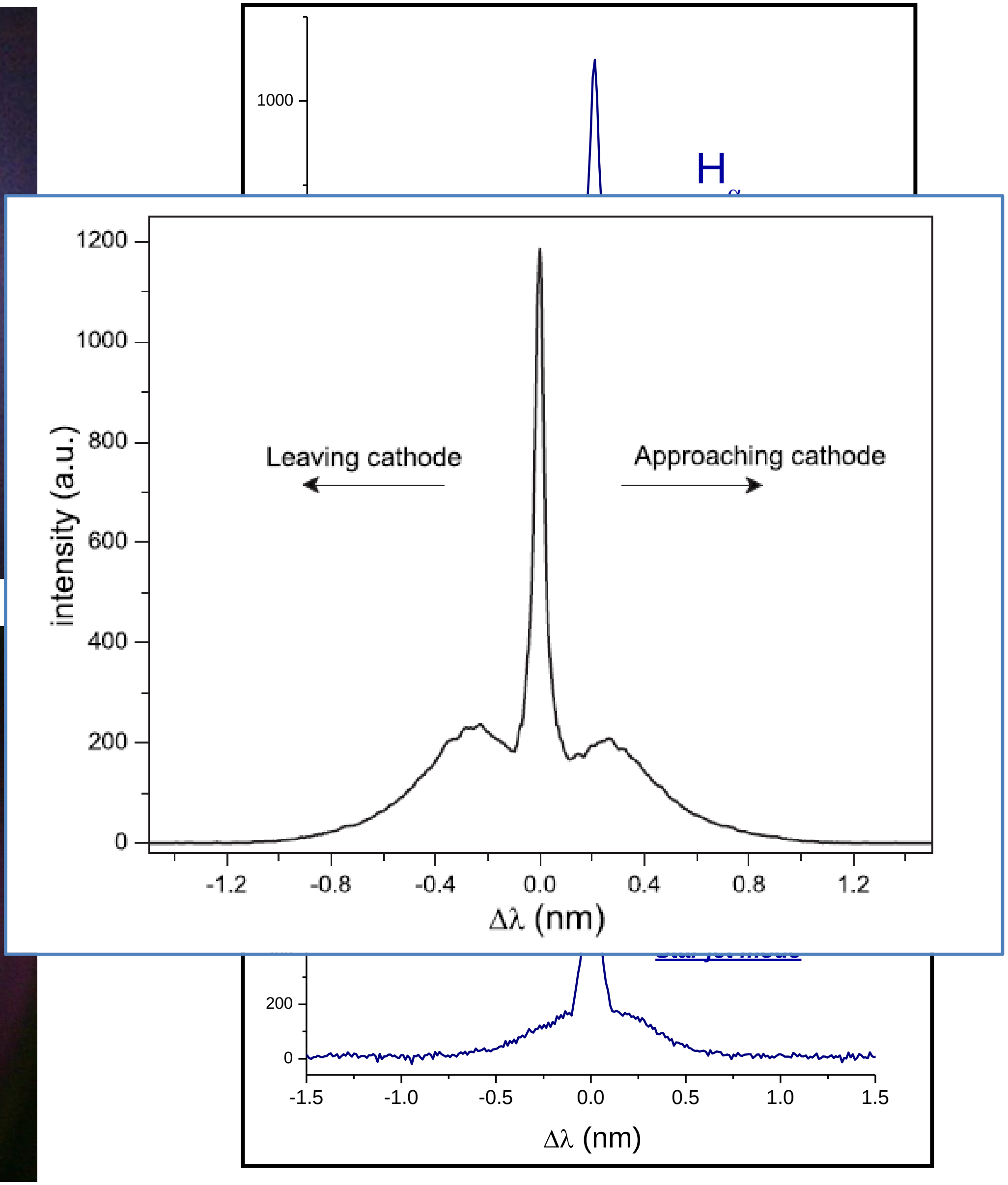


High energy plasma source
$T_e \approx T_{ion} \approx 20000K$
Plasma velocity ~100 km/s
B≈ 1T,
I=80 kA

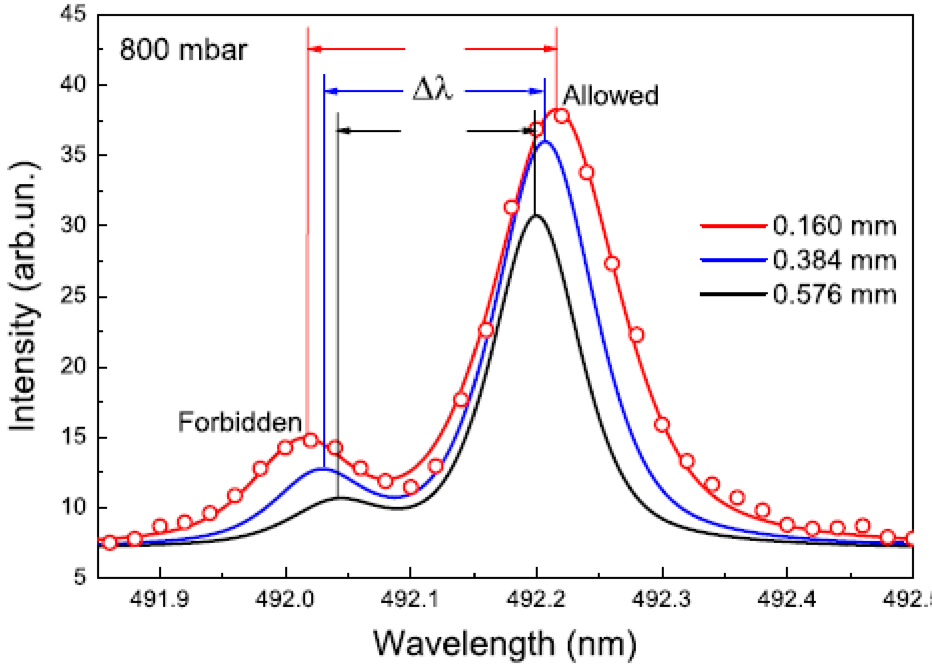
Electrostatic plasma confinement







Various types of Dielectric barrier discharges



COMPLEX LINE SHAPES IN NON-THERMAL LABORATORY PLASMA

N. Cvetanović, B.M. Obradović

Faculty of Physics, University of Belgrade

SLSLS 2023, Bajina Bašta

Introduction – features of Plasma:

- Non-thermal, or cold, atmospheric discharges have recently emerged as the most investigated and most promising laboratory plasma sources. In the last two decades they have been extensively studied both theoretically and experimentally.
- Plasma is strongly out of equilibrium with electron temperature of the order 10000 K while ions and atoms are at close to room temperature.
- The conditions for microreveresiblity are mostly not fullfed, and corona equilibrium guides the emissions.
- Plasma is always developing in time on various scales from ms to ns.
- It is inhomogeneous in space and time often (filaments or streamers) with sheaths near the electrodes.
- All this burdens diagnostic tasks and often the only choice is optical spectroscopy.

Line shapes:

- Doppler broadening is small (pm) Tg=350-500 K
- Van der Waals broadening often dominates the profile due to high pressure – 1 atm or even higher, at room temperature.
- Local field approximation is valid, so line intensity is determined by local electric field and electron density:

$$I = const. \cdot S(E) \cdot n_e$$

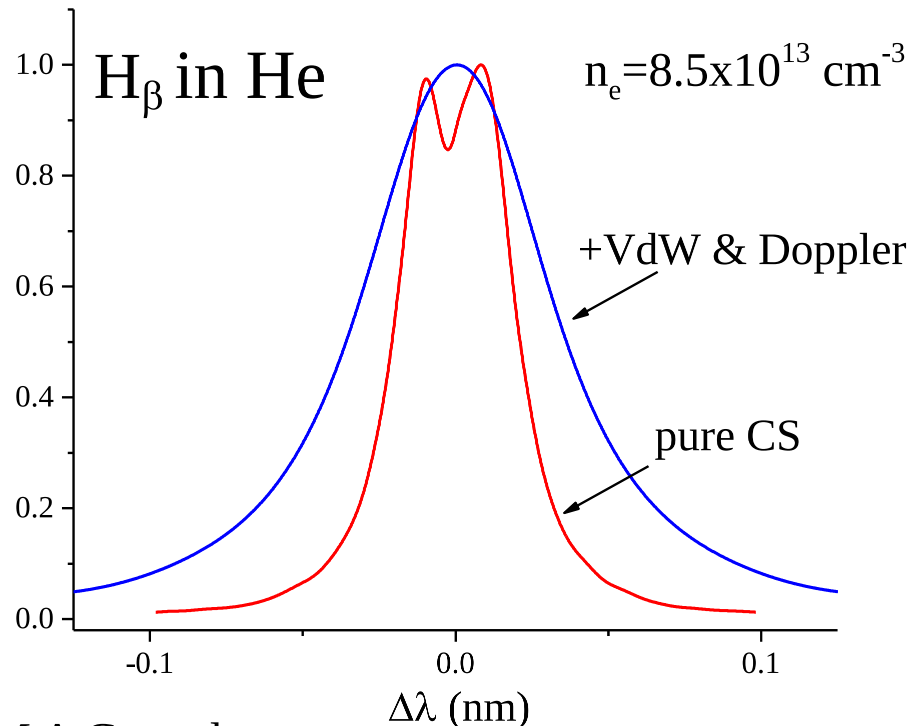
- Line is broadened both by micro and macro-fields so there is Stark broadening and Stark spiting, sometimes simultaneously.

- Knowledge of gas temperature and pressure is crucial to extract Van der Waals $\sim p\cdot T^{-0.7}$
- Below plasma density of 10^{14} cm^{-3} fine structure must be taken into account.

***Voigt approximation*:**

$$w_V = w_L/2 + \left((w_L/2)^2 + {w_G}^2\right)^{1/2}$$

$$w_L = w_S + w_{VdW} + w_R$$



Computer simulation, new results by M A Gonzalez

Nikiforov et al. *Plasma Sources Sci. Technol.* 24 (2015) 034001

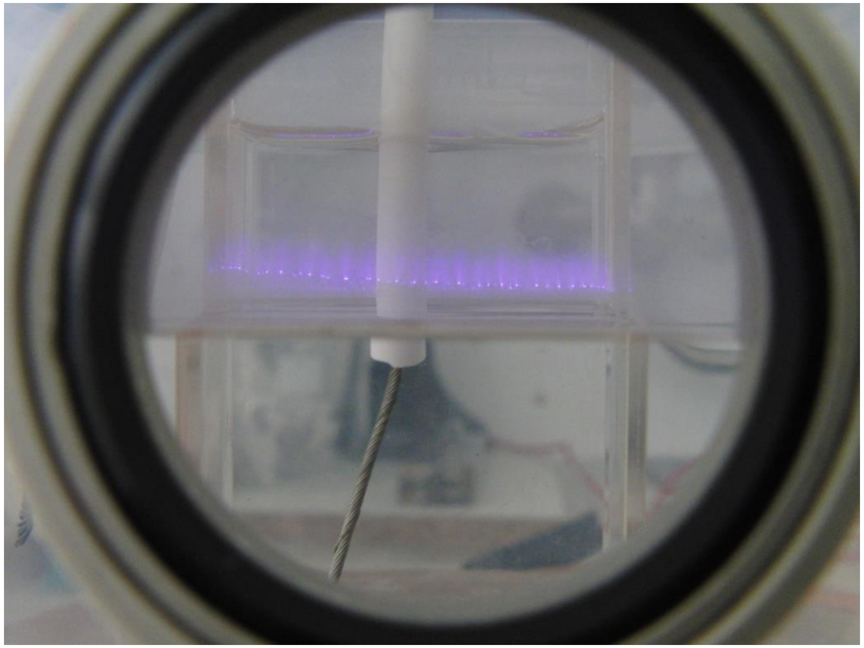
Gigosos et al. *Spectrochim. Acta Part* B 58 (2003) 1489

Problems in line analysis:

- Space inhomogeneity and Transient nature – fast time development of these plasmas pose limitations on line profile analysis.
- Similarly to astrophysical plasmas, complex spectral line shapes are occasionally observed, that cannot be explained using standard models for line shape analysis e.g. Doppler or pressure broadening.
- Advanced fitting procedures must be developed, often paired with fast imaging and electrical measurement to complete the unknowns in the method.
- The inhomogeneity of plasma in time in space, presence of strong sheaths, and line-of-sight effects are mirrored in the shape of the spectral line.

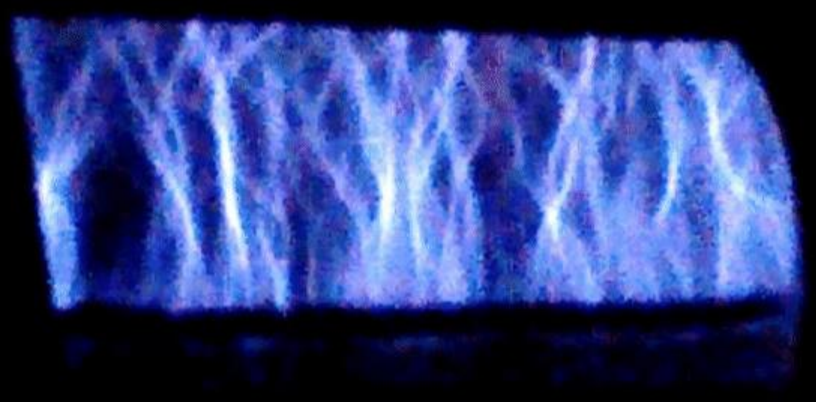
SDBD with liquid electrodes

- Surface discharge configuration with liquid electrodes
- A dielectric cuvette is immersed in the liquid and the plasma develops along its outer surface between the two liquid levels.
- It operates with different gas flows: Ar, N_2, Air



Argon plasma above liquid

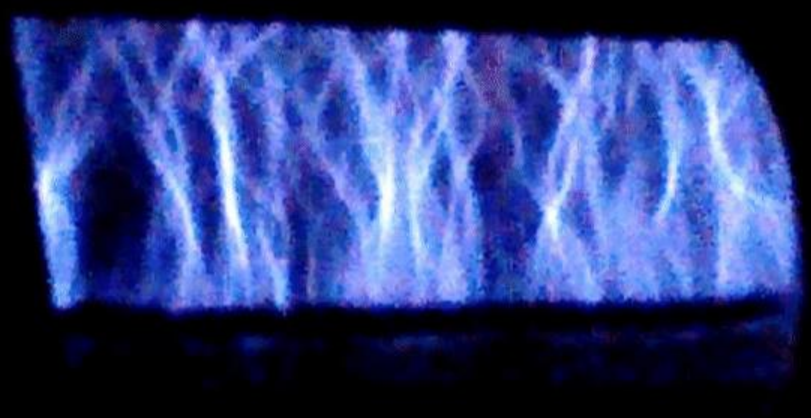
Video frame rate 30 fs/s



- Cold mode: long branching microdischarges, high acoustic noise
- Hot mode: more stable, shorter filaments, low noise

Argon plasma above liquid

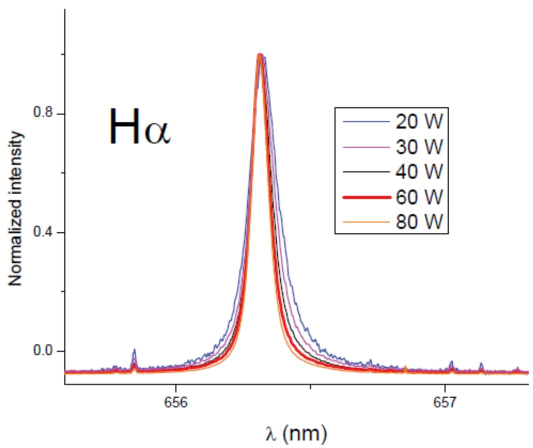
Video frame rate: 1 fs/s

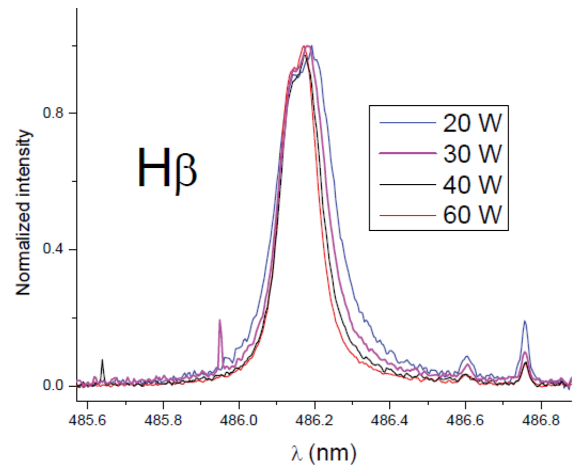


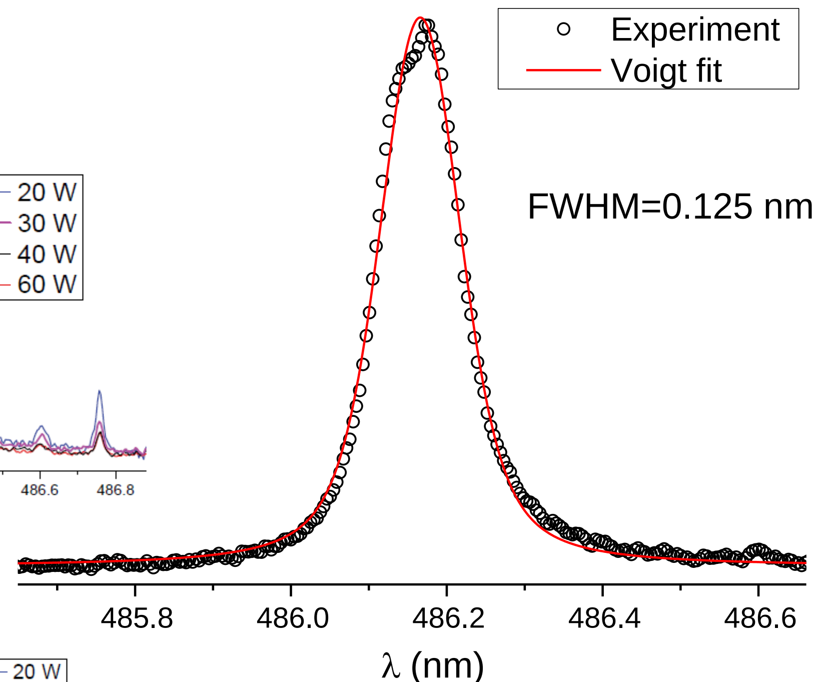
Line radiation is integrated over a large number of current pulses and involves a spatial intensity distribution over an inhomogeneous and small plasma volume.

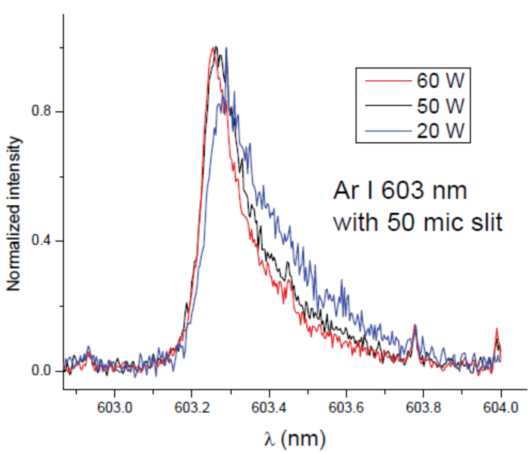
Line profiles (time integrated)

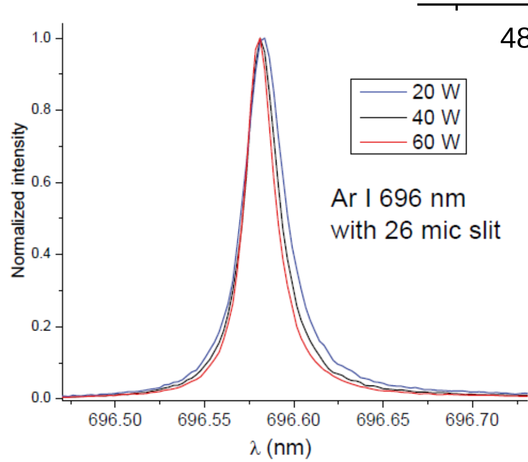
- Instrumental FWHM=0.017 nm ,
- Van der Waals broadening calculated from gas temperature , typically for H $w_{VdW} \approx 0.07$ nm





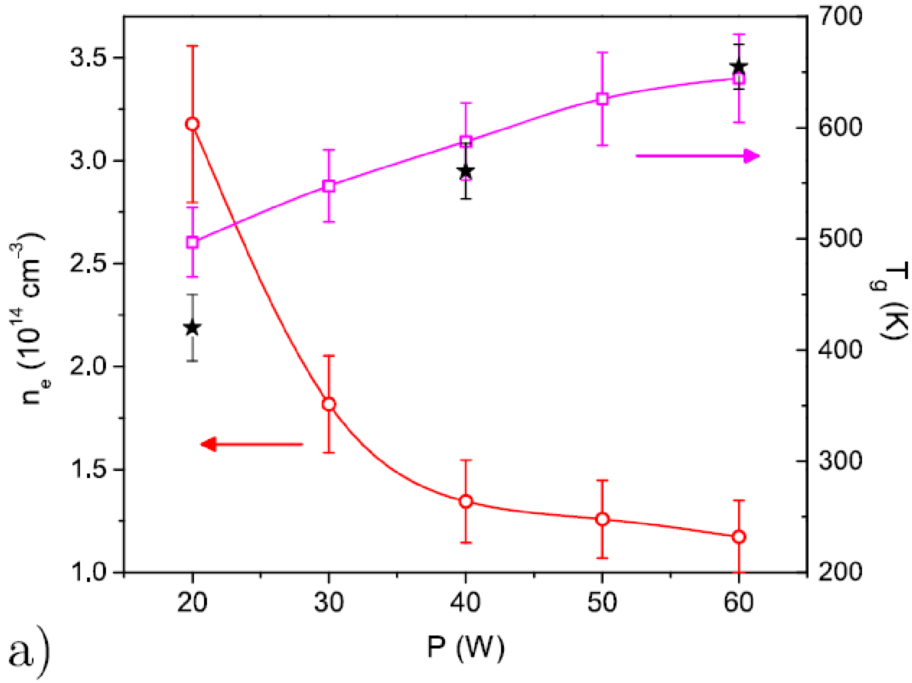


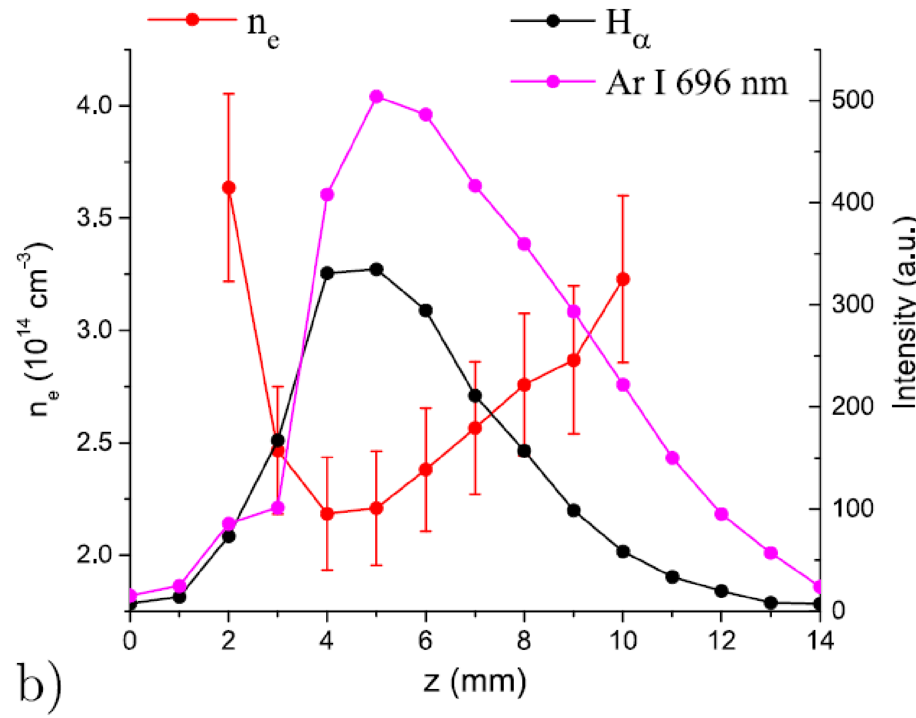




- Asymmetric shapes indicate two-density plasma.

Time integrated results





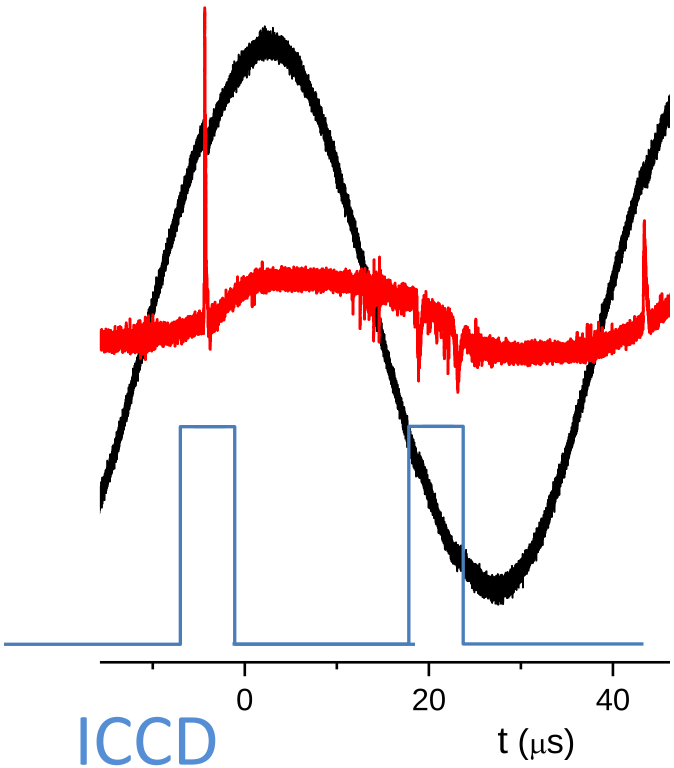
- Gas temperature calculated from width Ar I 710 nm and OH band
- Electron density from H_β

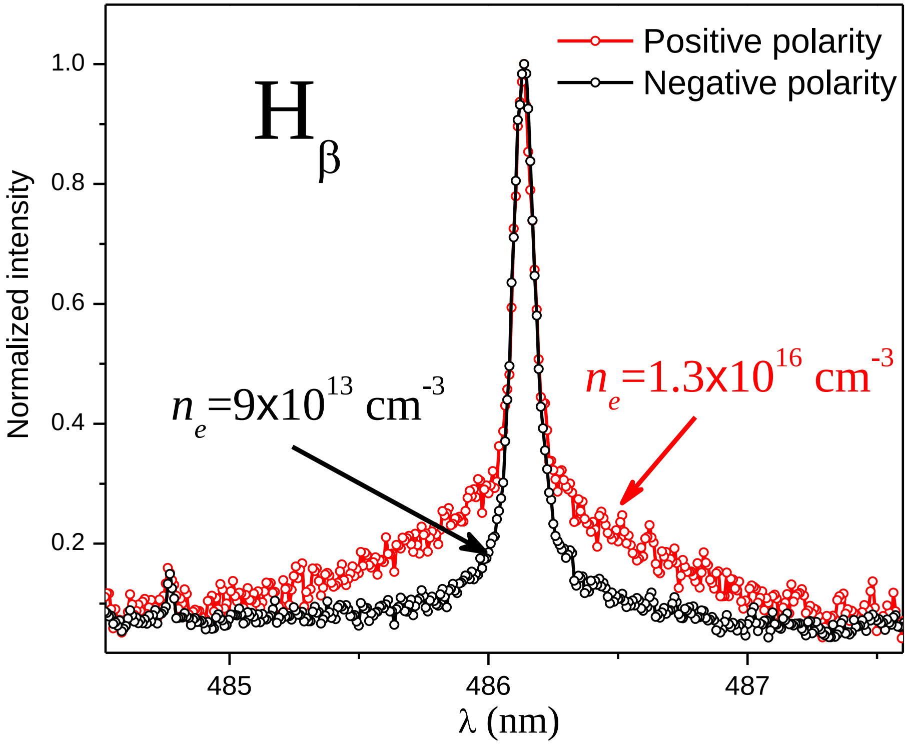
Cvetanovic et al. *Plasma Sources Sci. Technol.* 27 (2018) 025002

Time-selective measurements of two polarities

Two polarities were studied separately with a time window of 6-8 μs.

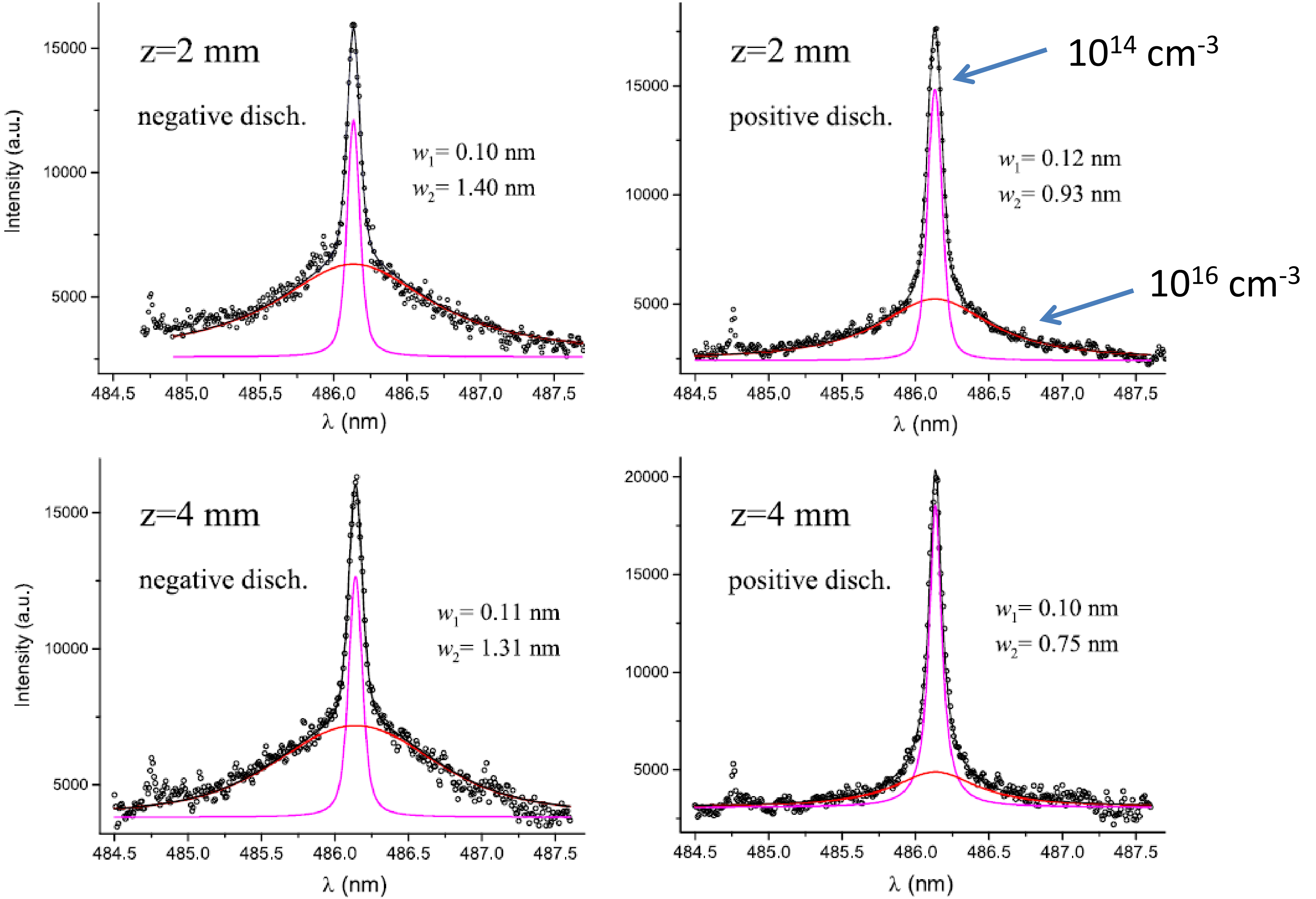
The aim was to examine the behavior of the negative and positive streamers.





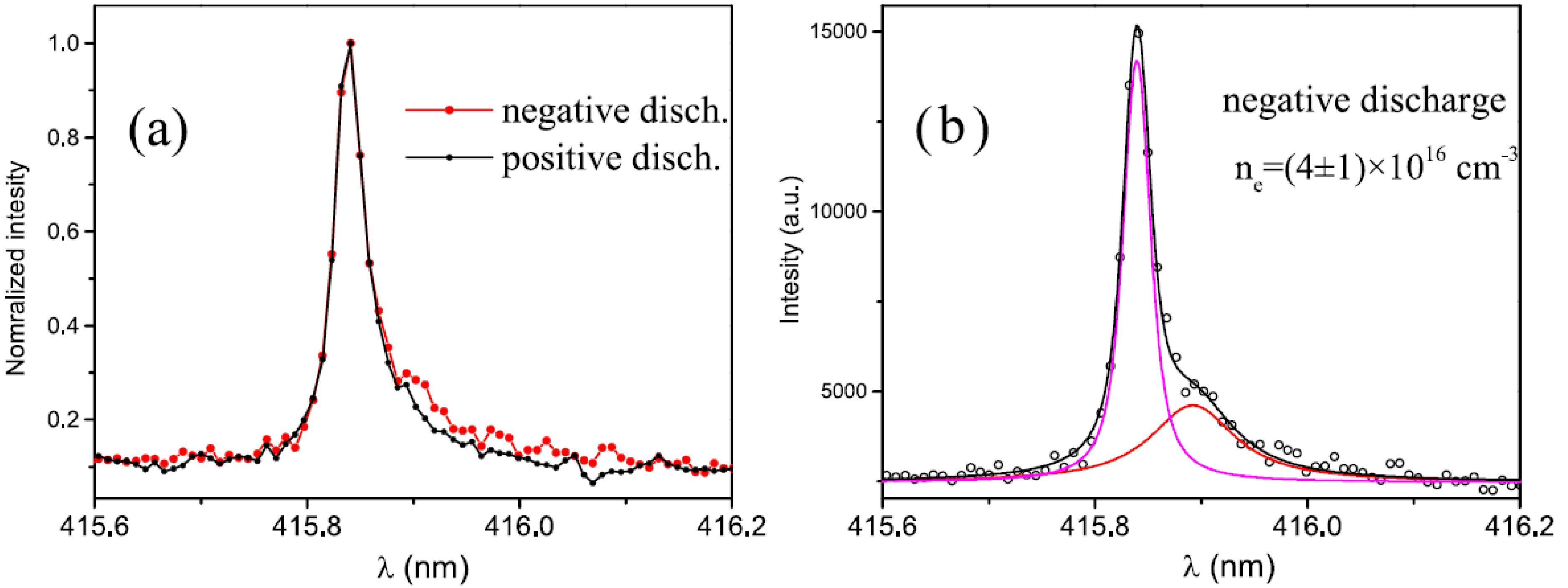
Very different profiles corresponding to very different plasma densities.

H_β “Cold mode”



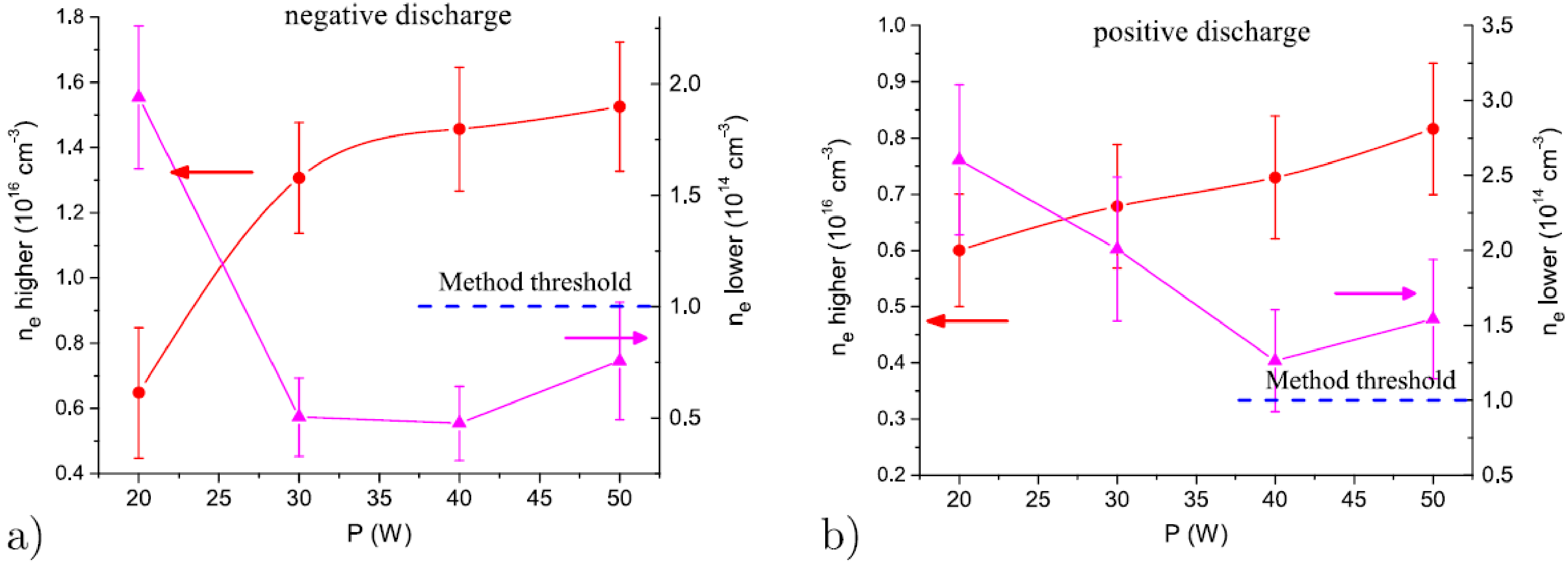
Cvetanovic et al. *Plasma Sources Sci. Technol.* 27 (2018) 025002

Ar I 416 nm "Cold mode"



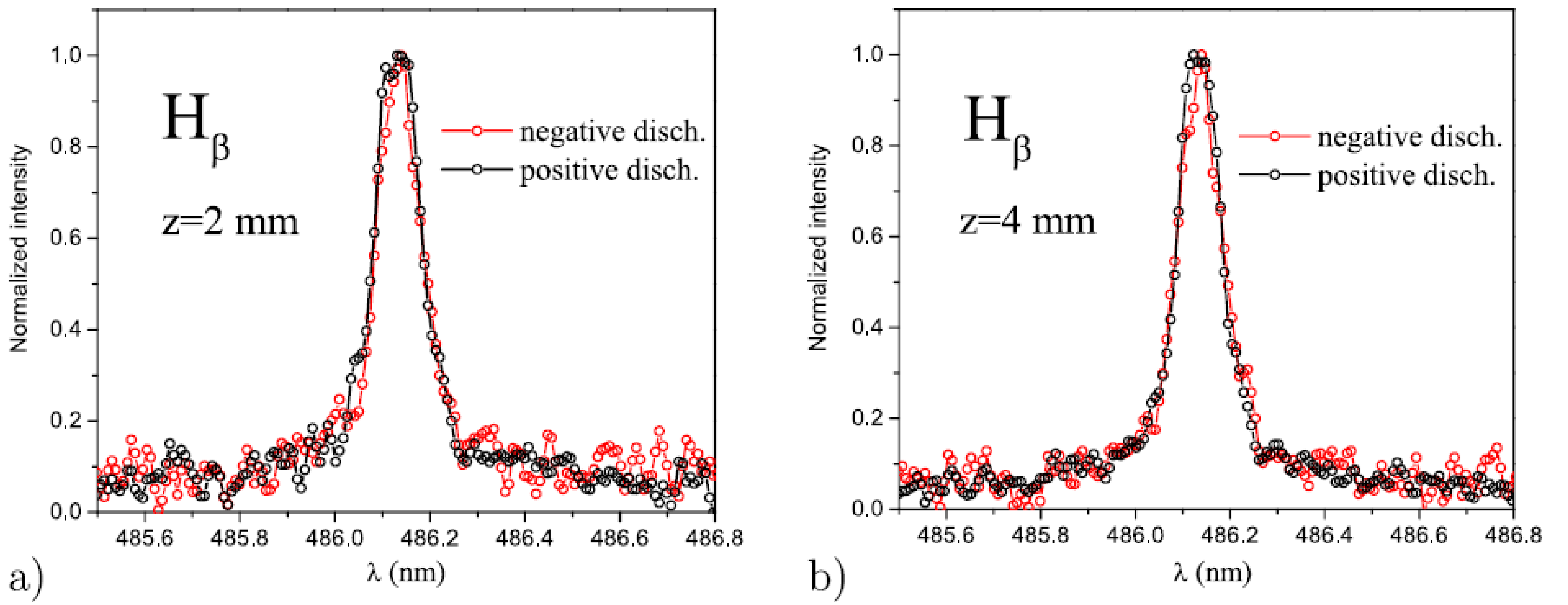
Cvetanovic et al. *Plasma Sources Sci. Technol.* 27 (2018) 025002

“Cold mode”



Cvetanovic et al. *Plasma Sources Sci. Technol.* 27 (2018) 025002

“Hot mode”



- No significant change with polarity
- Much smaller density

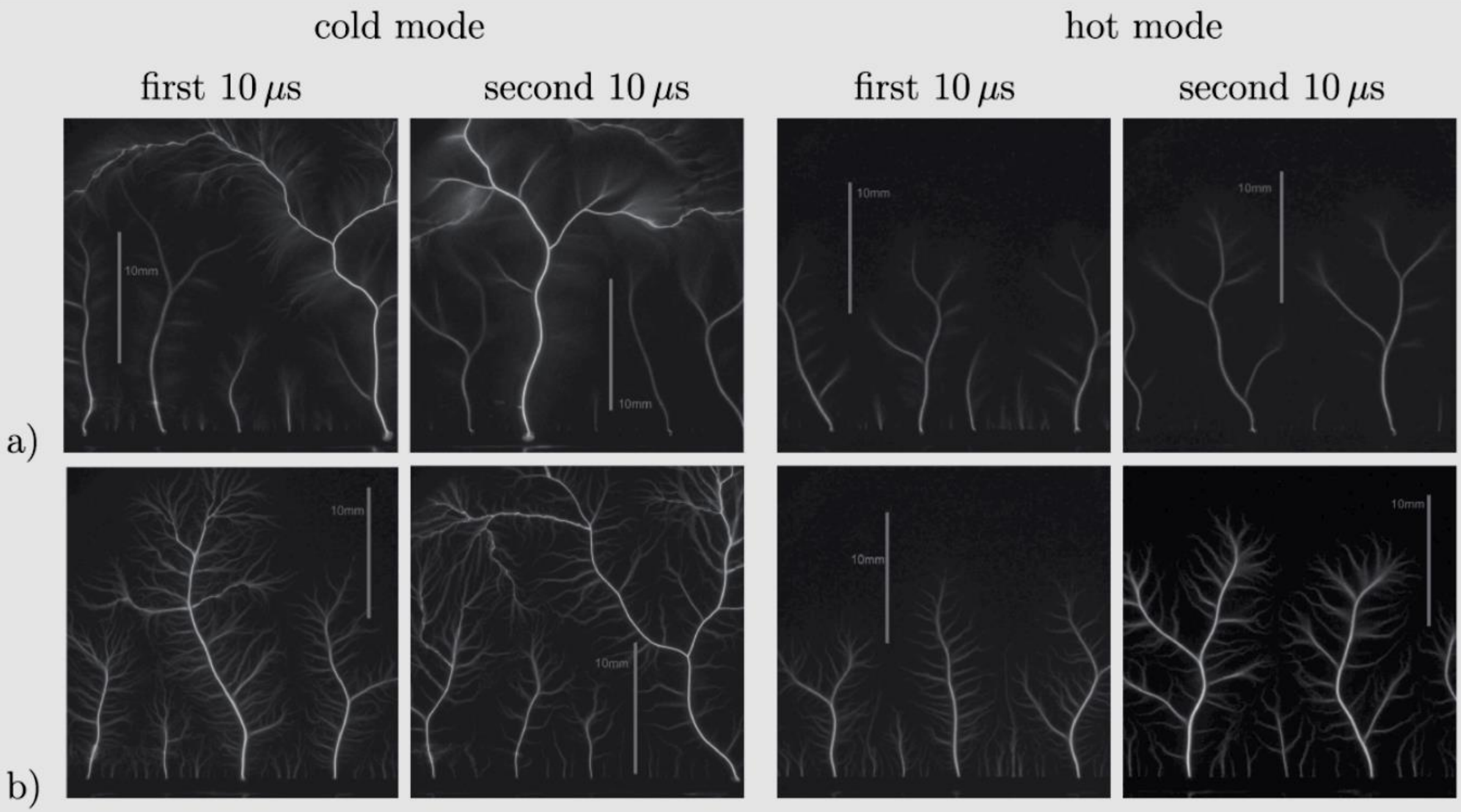
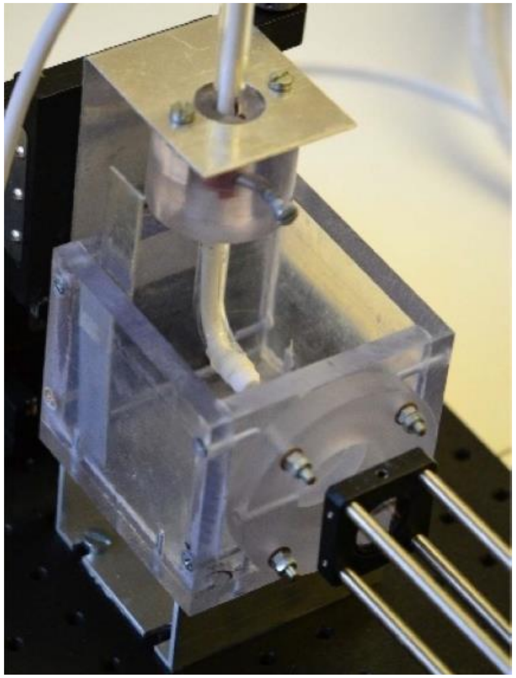
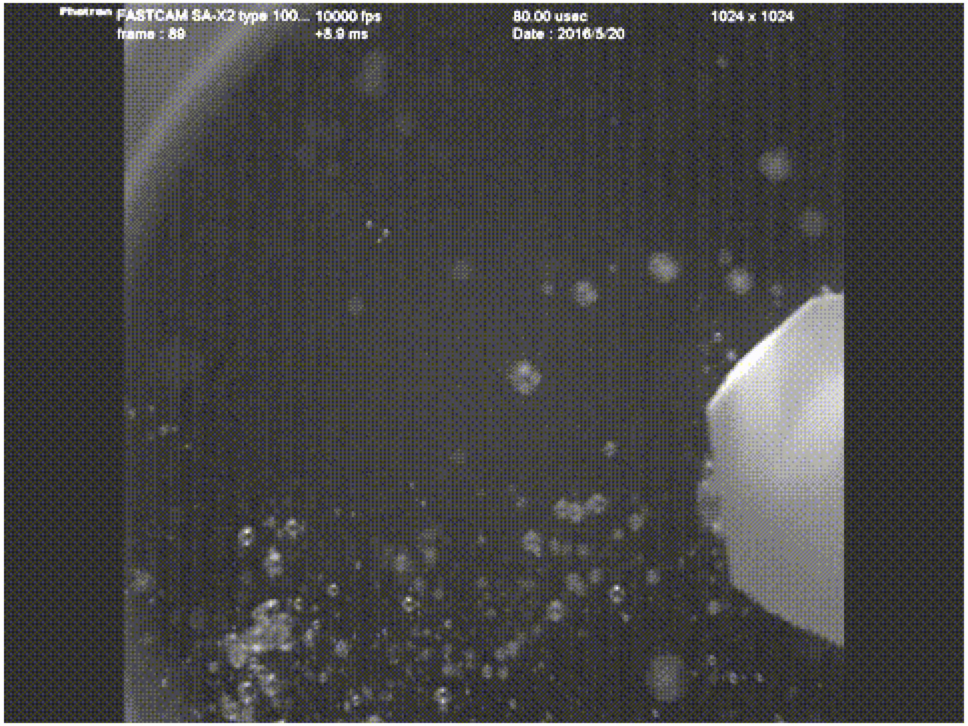


Figure 3. Imaging of the negative, row (a), and positive, row (b), discharges for the first and the subsequent 10 μs during the active phase of the *cold* and *hot* modes for average power of 50 W. The vertical line in each inset represents the scale of 10 mm. The ICCD camera openings for both polarities are depicted in figure 2.

Cvetanovic et al. *Plasma Sources Sci. Technol.* 27 (2018) 025002

Pin-hole based plasma source for discharge in liquids

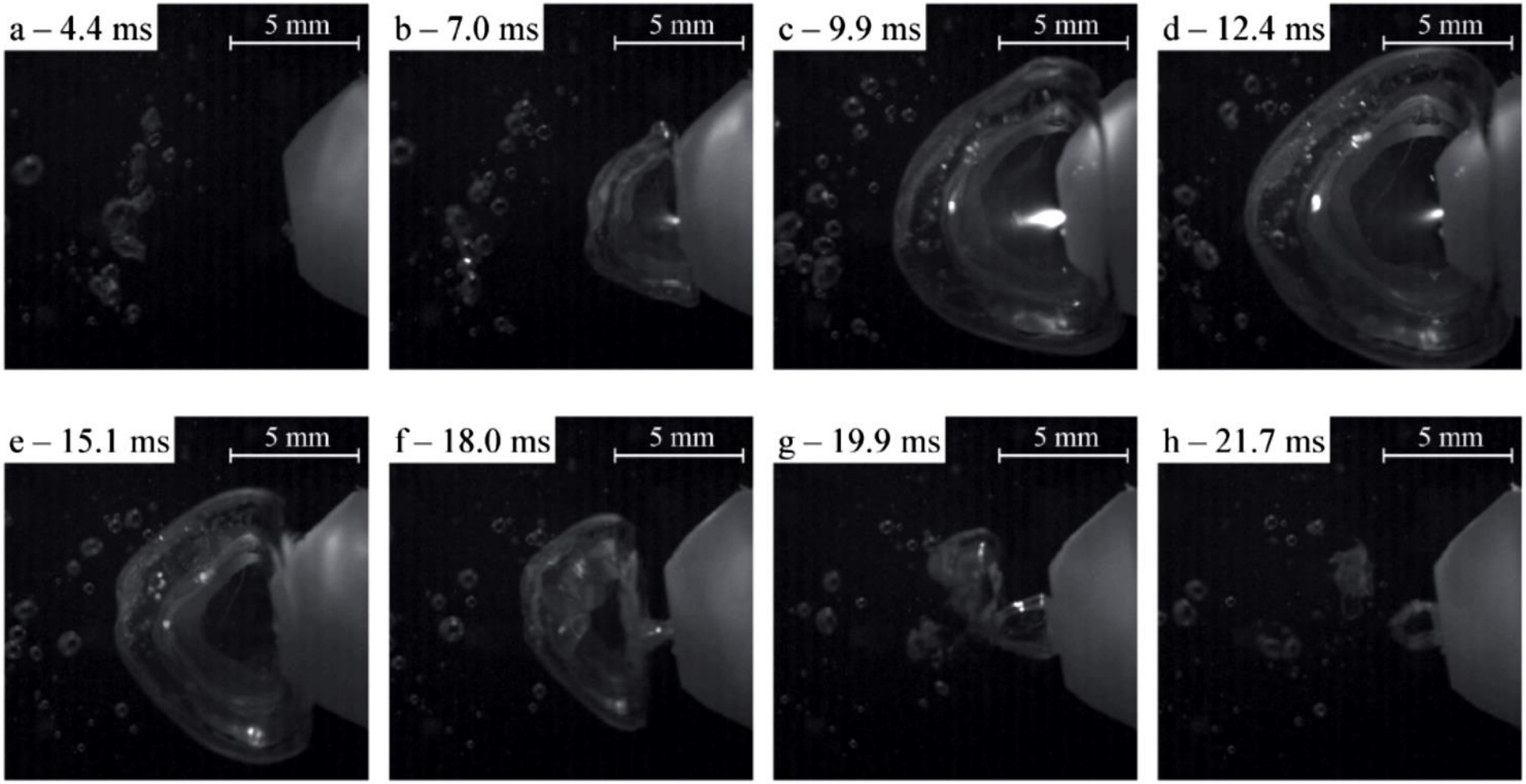




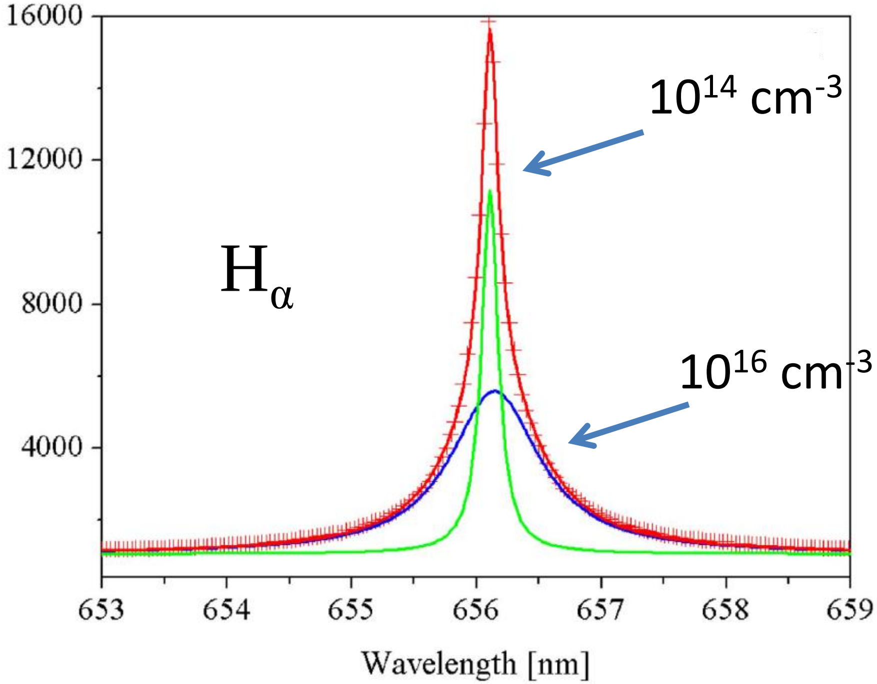
A shock wave is formed with pressure ranging 2-16 MPa

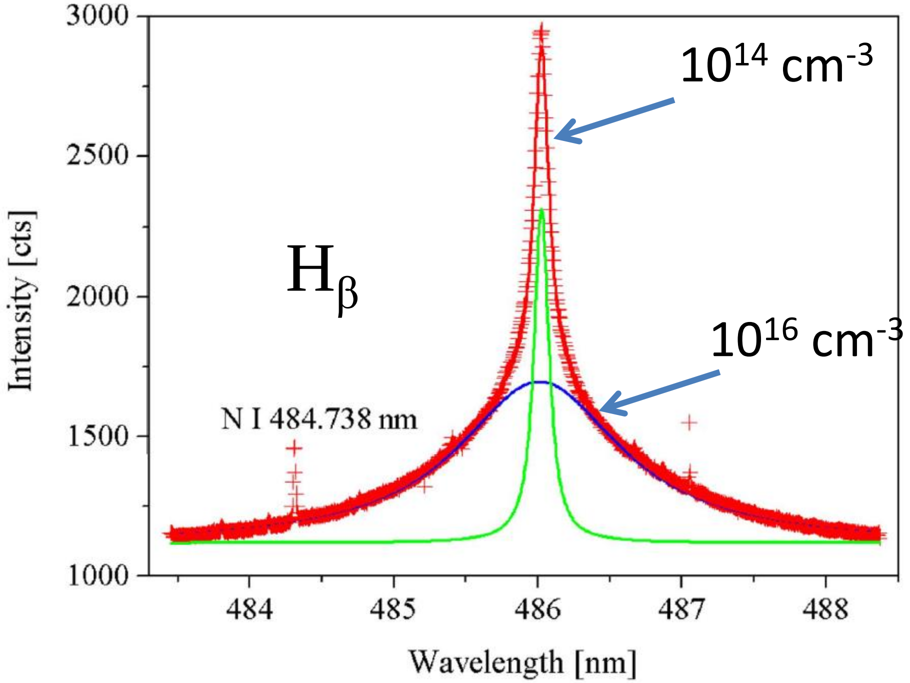
Krcma et al. *Plasma Sources Sci. Technol.* 27 (2018) 065001

Plasma is formed inside the gas bubble (self-pulsing occurs).



Krcma et al. *Plasma Sources Sci. Technol.* 27 (2018) 065001





- The recorded line profiles are time averaged over discharge evolution.,
- n_e changes by more than two orders of magnitude.
- A two component profile is an approximation.

Krcma et al. *Plasma Sources Sci. Technol.* 27 (2018) 065001

Pressure and gas composition inside the bubble are unknown

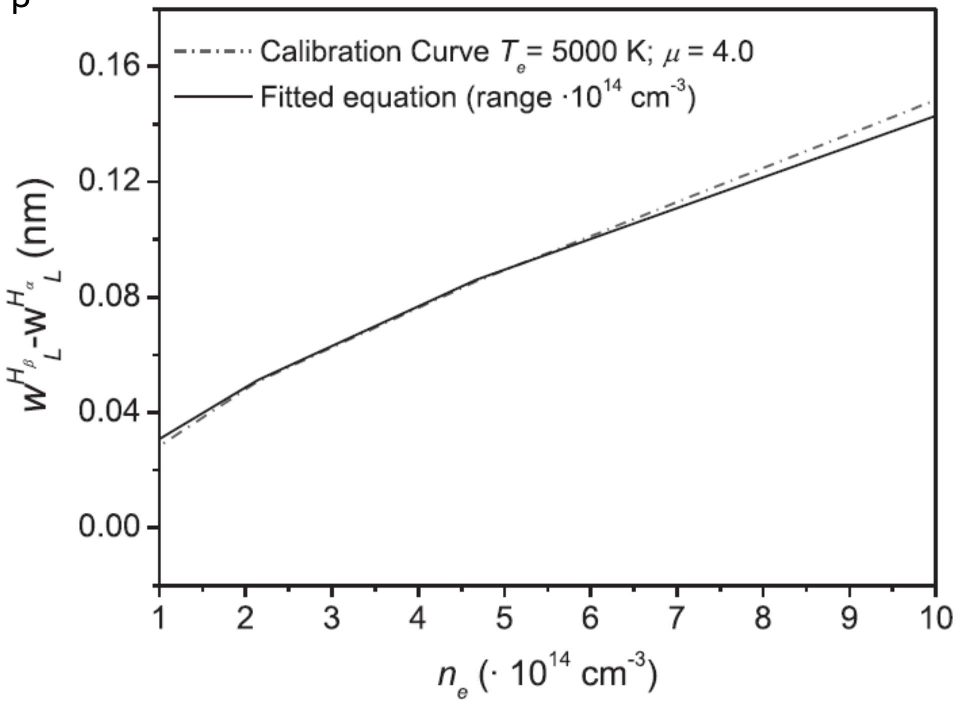
Method by Dimitrijević & Yuberoa

Yuberoa et al. *Spectrochim. Acta Part B* 107 (2015) 164

Van der Waals broadening is similar in H_α and H_β:

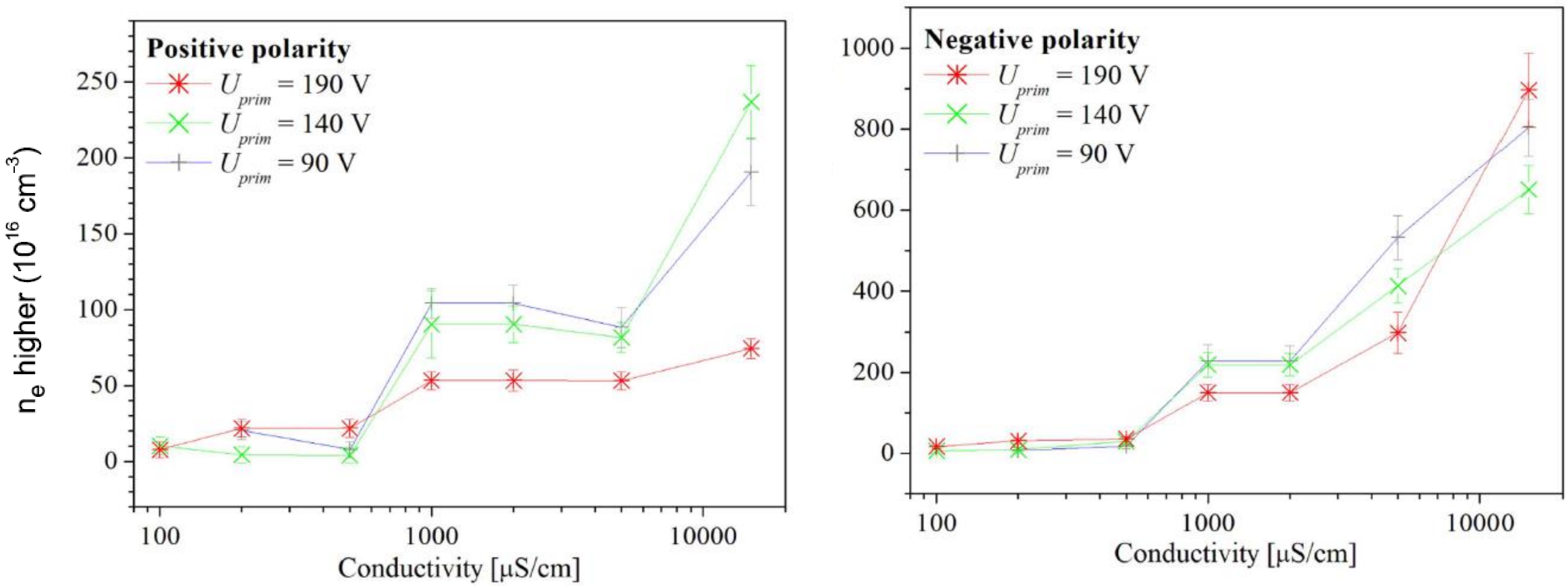
$$w_W^{H_\alpha}\left(T_g\right) = 18.67\,C/T_g^{\frac{7}{10}}\left(\cdot 10^9\,\text{nm}\right)$$

$$w_W^{H_\beta}\left(T_g\right) = 17.97\,C/T_g^{\frac{7}{10}}\left(\cdot 10^9\,\text{nm}\right)$$



The subtraction of Lorentzian widths eliminates the need for pressure information.

Pressure was subsequently estimated to 4-5 atm depending on the phase.

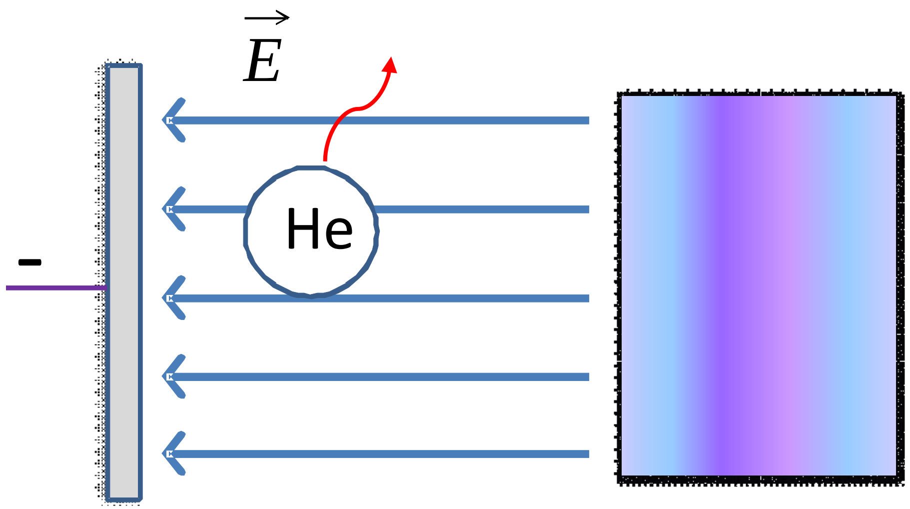


Krčma et al. *Plasma Sources Sci. Technol.* 27 (2018) 065001

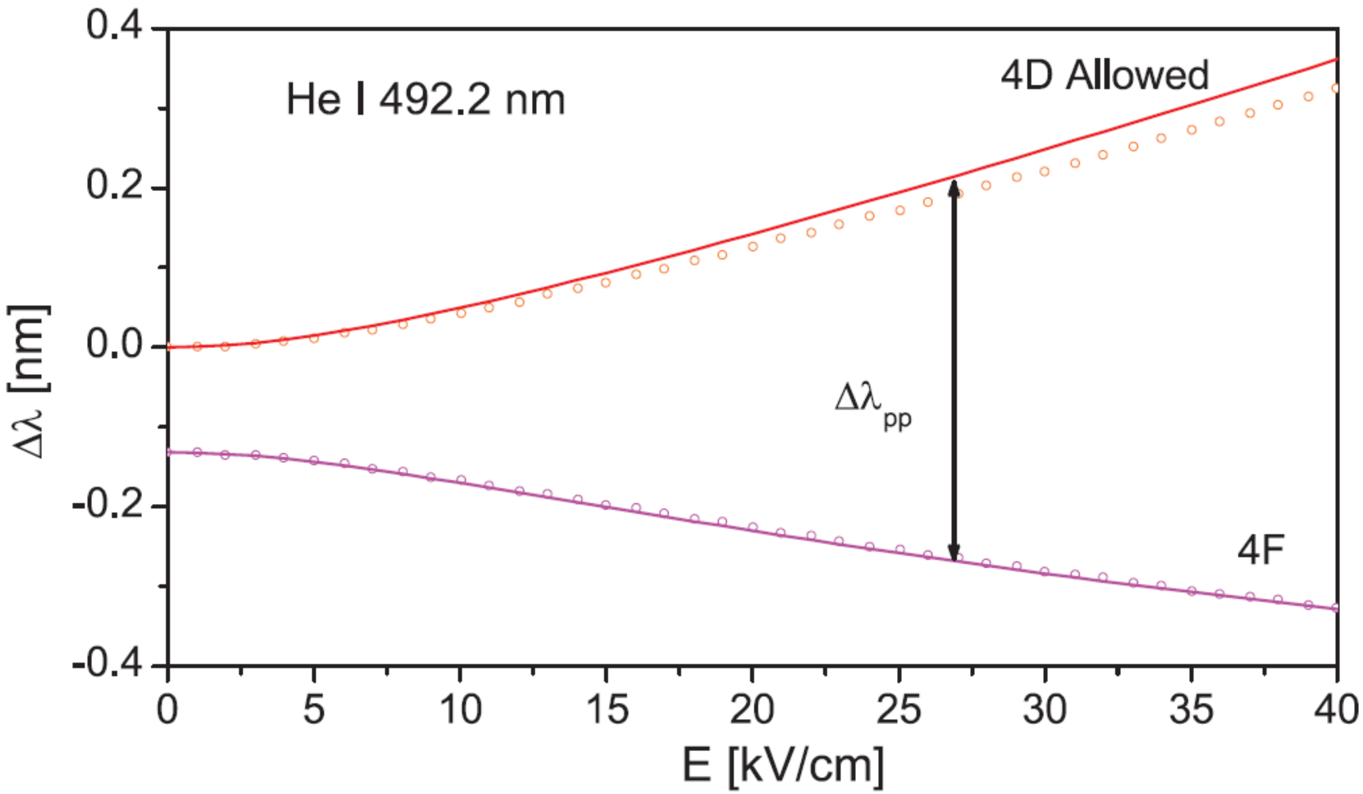
Stark spiting of He lines in strong fields

Stark polarisation method developed and used for two decades at Faculty of Physics by Kuraica and Konjevic (1997).

- Helium linear Stark effect: He I 492.2nm, 447.7 nm, 402 nm …
- Line shape depends on the discharge conditions (*T*, *p* etc.)

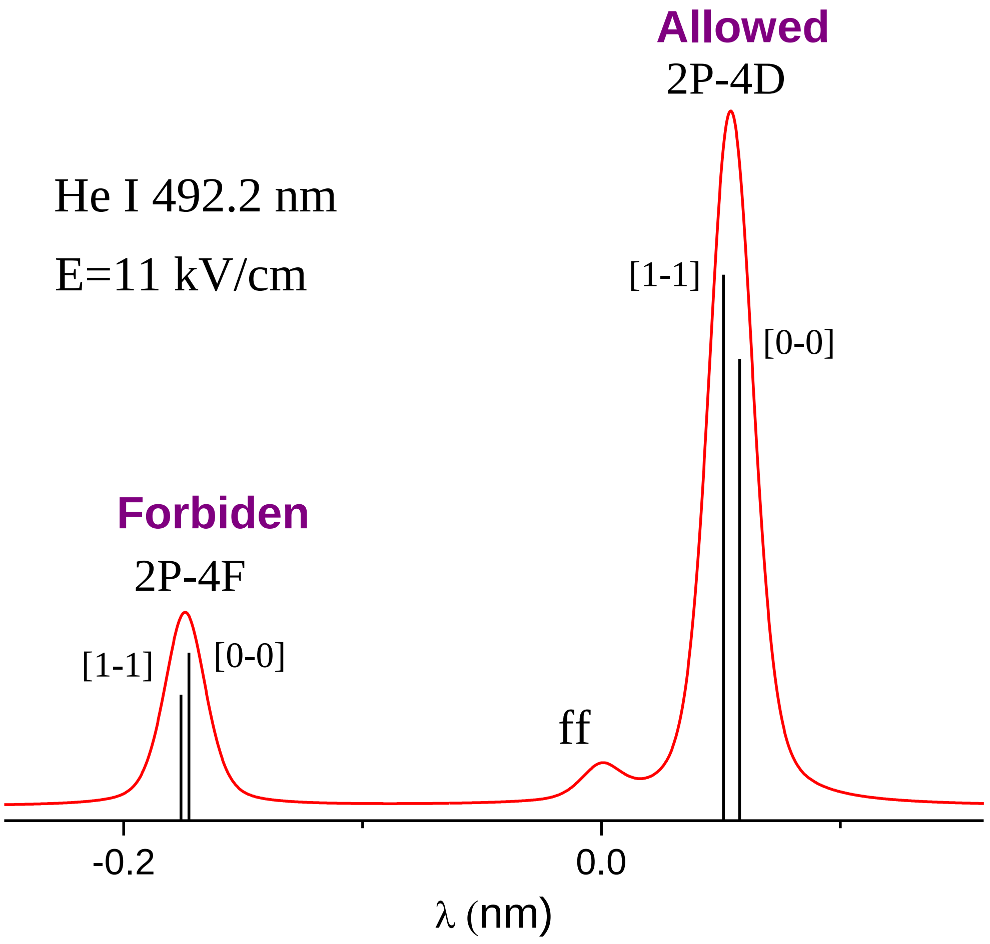


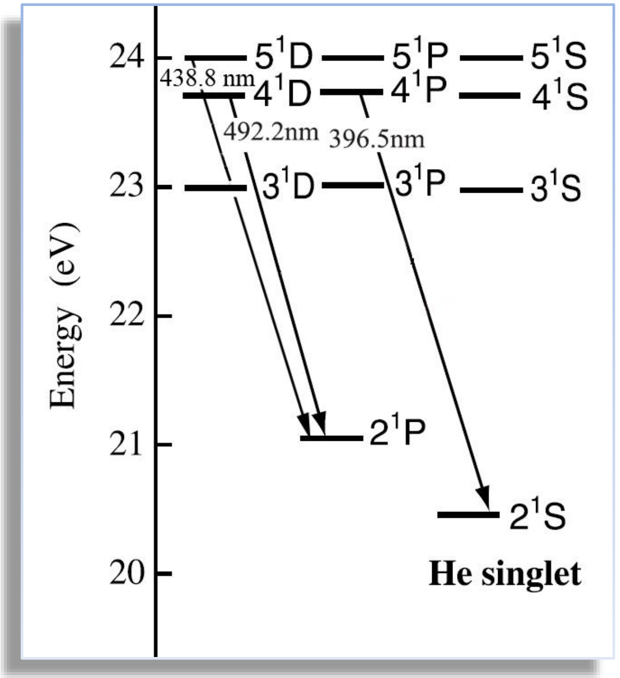
• Electric field determines wavelength separation and intensity ratio.



Cvetanović et al. *J. Phys D: Appl. Phys (2015)*

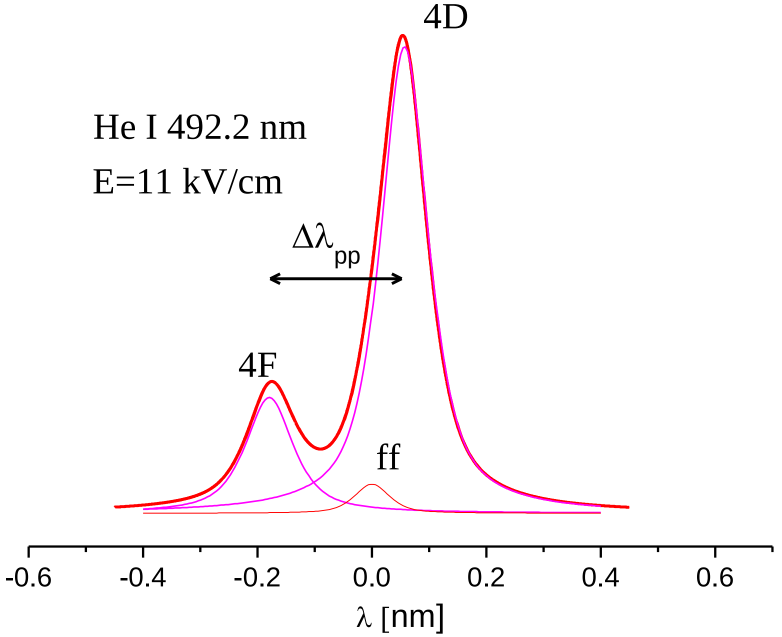
Stark shifting tested and method developed in low pressure glow discharge

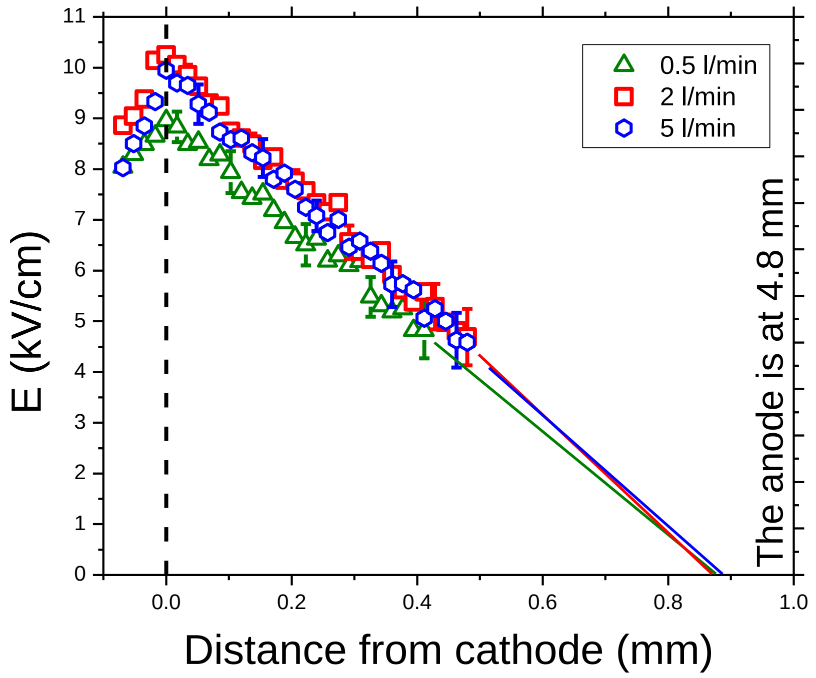


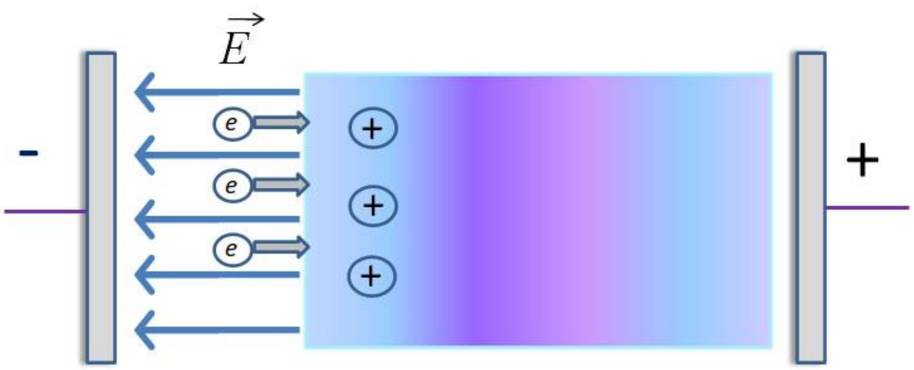


Cvetanović et al. *J. Phys D: Appl. Phys 2015*
Kuraica et al. *Appl. Phys. Lett.* (1997)

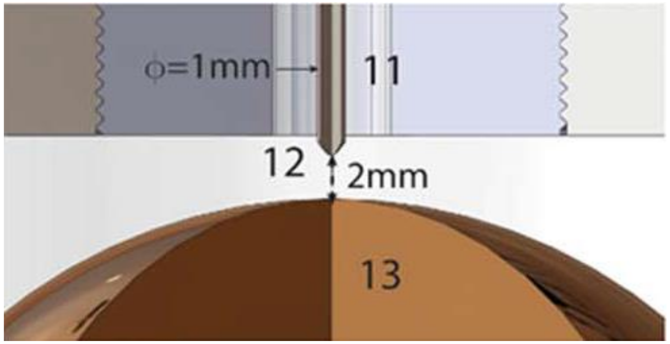
Example from a DBD discharge HeI 492 nm 1 atm





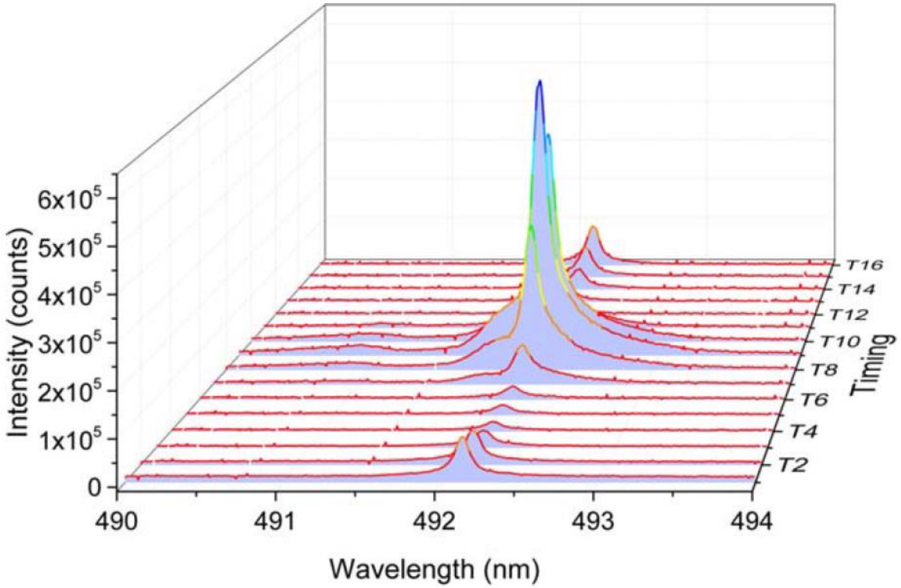


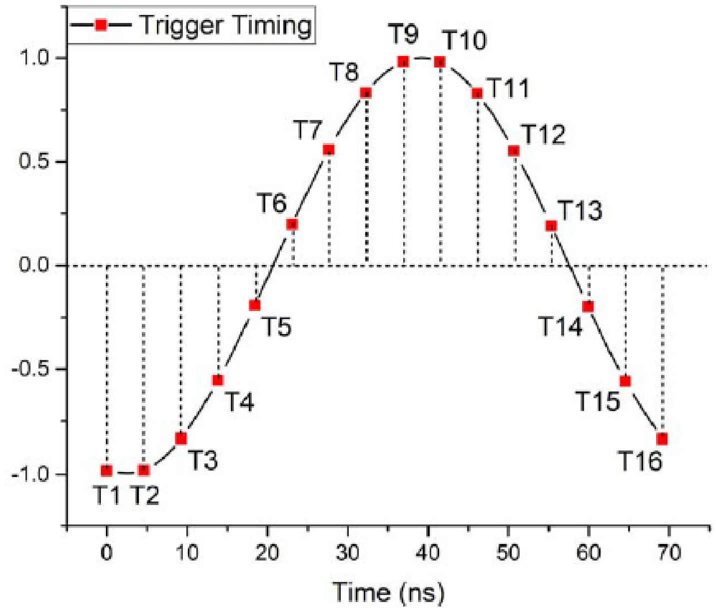
Atmospheric pressure RF discharge - coexisting α and γ-modes



Very narrow sheath <50 μm

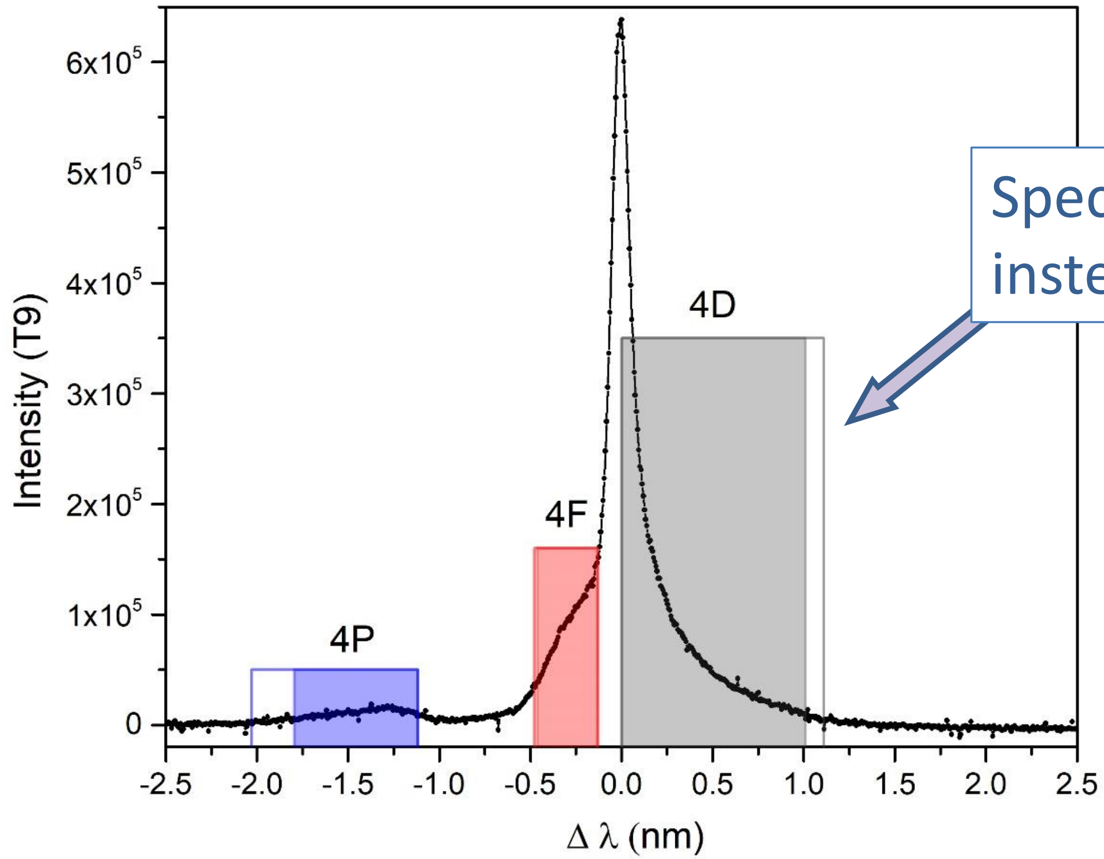
Very fast development ~10 ns





Wang et al. *Plasma Sources Sci. Technol.* 28 (2019) 055010

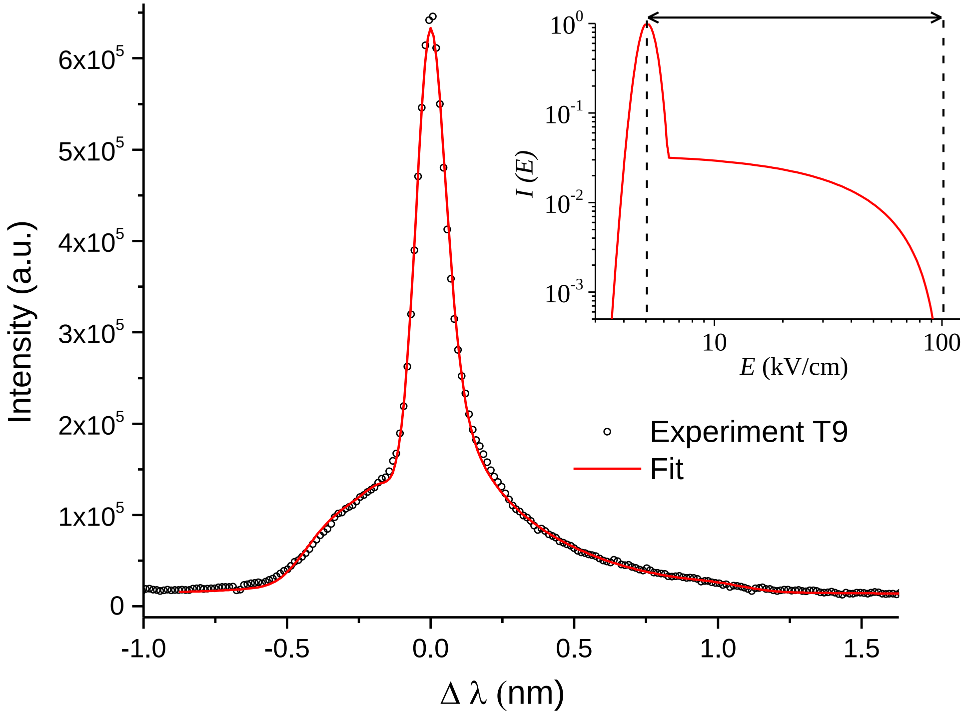
Surprising line shape spreading ~2 nm



Spectral distribution instead of a spectral line

The allowed He I 492 nm 4D and the forbidden 4F and 4P

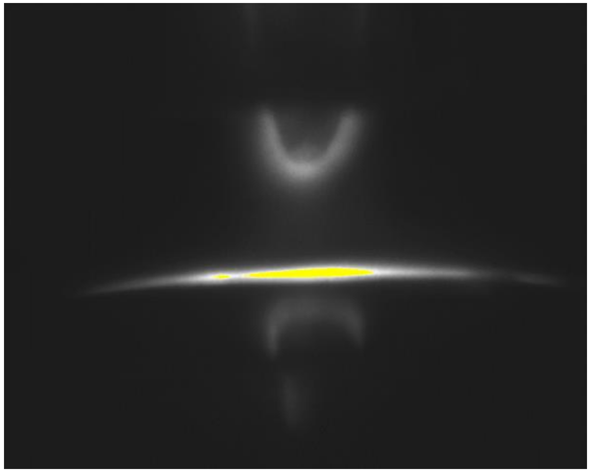
Due to the narrow sheath, the entire field distribution is summed up in the line profile



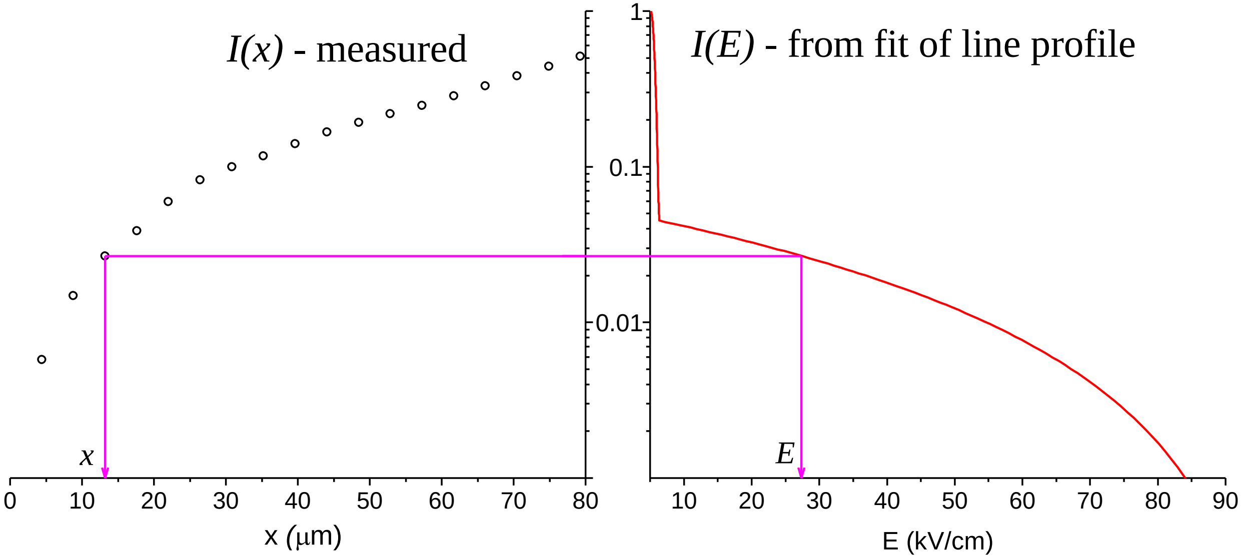
$$P(\lambda) = a \times \int_{E_{\mathrm{MIN}}}^{E_{\mathrm{MAX}}} I(E) \times S(E, l)\mathrm{d}E$$

$$= b \times \int_{0}^{L_{\mathrm{SLIT}}} I(x) \times S(E(x), l)\mathrm{d}x.$$

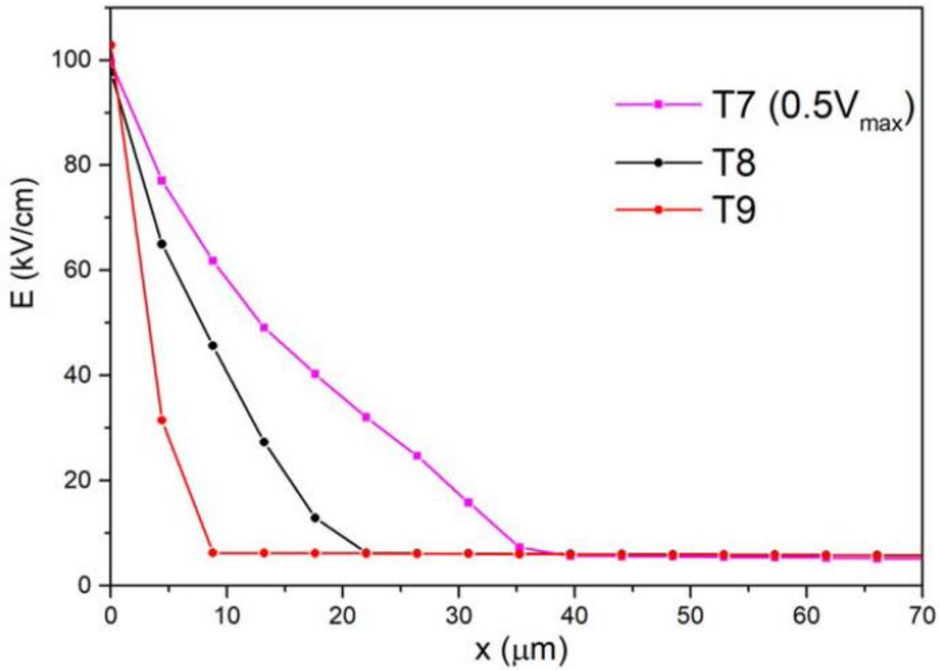
- Fitting procedure provides only *I(E)*
- *E(x)* must be reconstructed



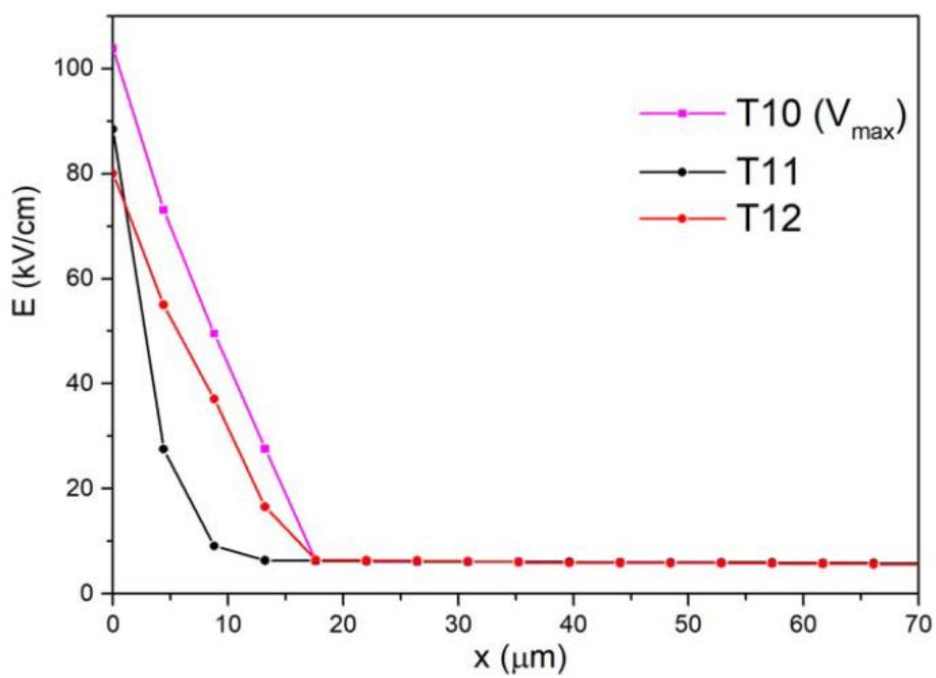
Numerical procedure:
Using fast imaging to reconstruct the field distribution at a given time instance.



Wang et al. *Plasma Sources Sci. Technol. 28 (2019) 055010*

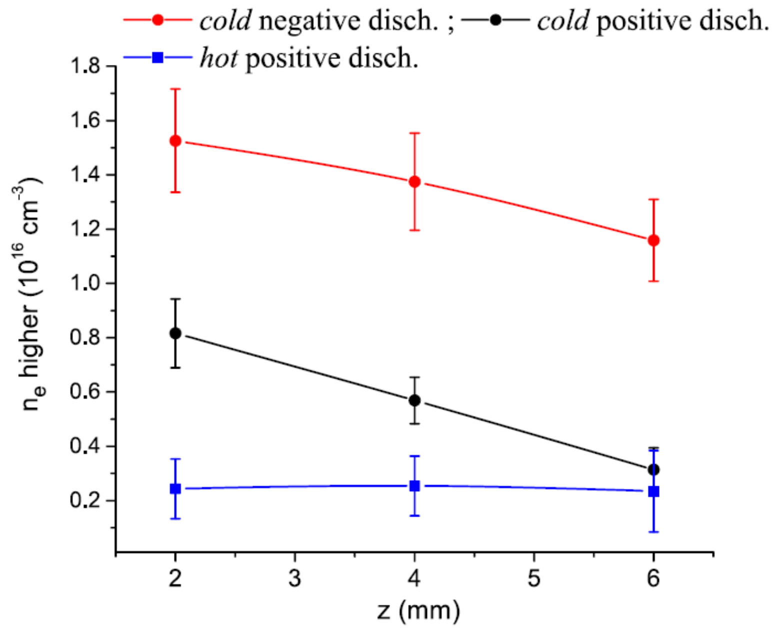


E (kV/cm)
x (μm)
T7 (0.5V_{max})
T8
T9

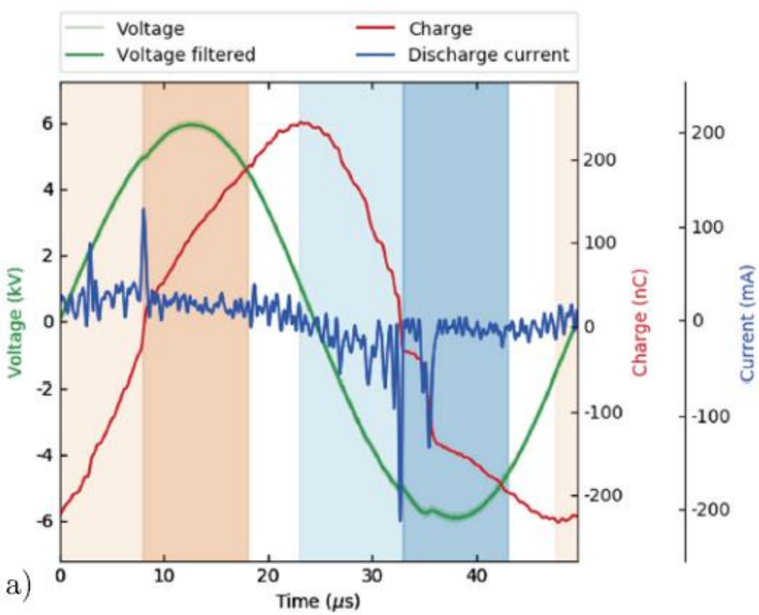


E (kV/cm)
x (μm)
T10 (V max)
T11
T12

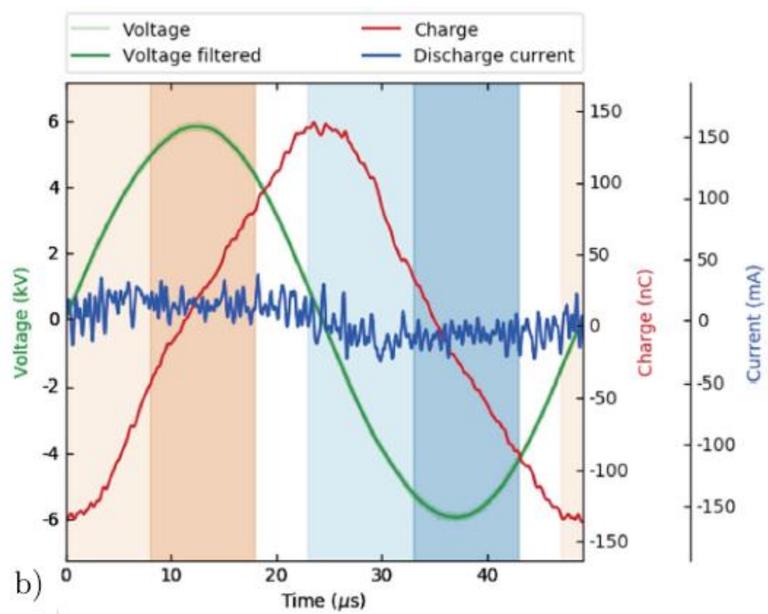
Thank you for your attention


cold negative disch. ; cold positive disch.
hot positive disch.
n_e higher (10^16 cm^-3)
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
2
3
4
5
6
z (mm)

Cold


Voltage
Voltage filtered
Charge
Discharge current
Voltage (kV)
Charge (nC)
Current (mA)
Time (μs)
a)

Hot


Voltage
Voltage filtered
Charge
Discharge current
Voltage (kV)
Charge (nC)
Current (mA)
Time (μs)
b)