Plasma assisted high pressure combustion; surface HP nanosecond DBD

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PC2A, Lille:
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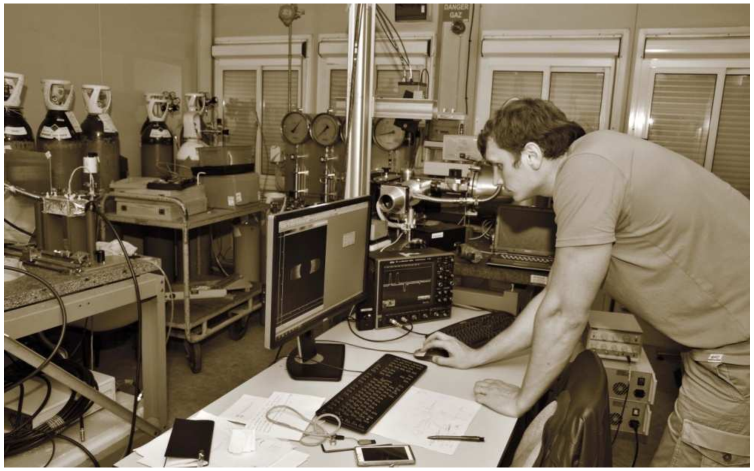
Pascale Desgroux



Plan of the presentation

Introduction: physics and chemistry of plasma-assisted combustion

Shock tube experiments: 0D, low pressures, high temperatures

Rapid compression machine (RCM) experiments: 2D, high pressures, low temperatures

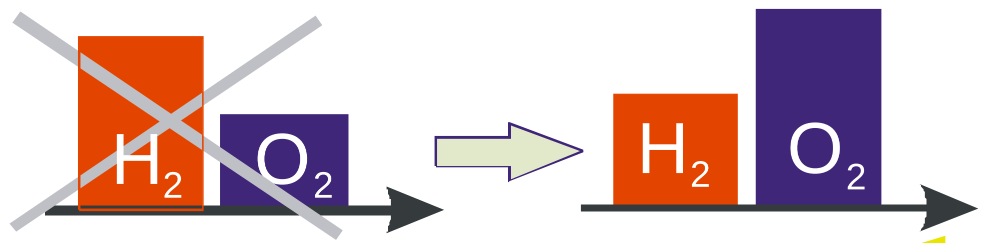
High pressure high temperature (HPHT) discharge cell experiments: the discharge and the following combustion

High pressure discharge: streamer-to-filament transition

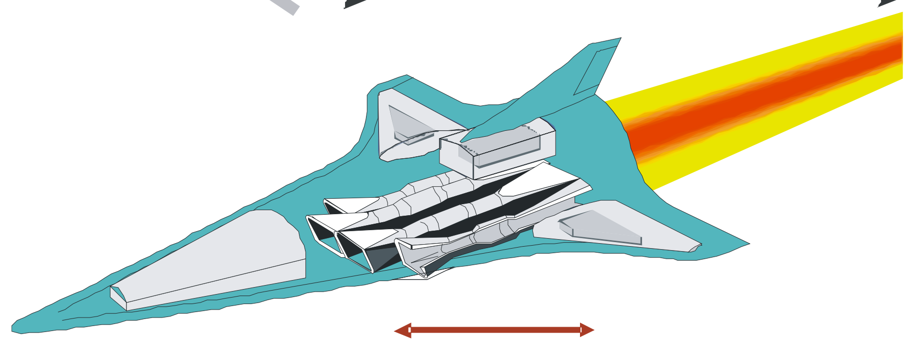
I. Physics and chemistry of plasma assisted combustion

Plasma assisted ignition/combustion: nonequilibrium plasma applications

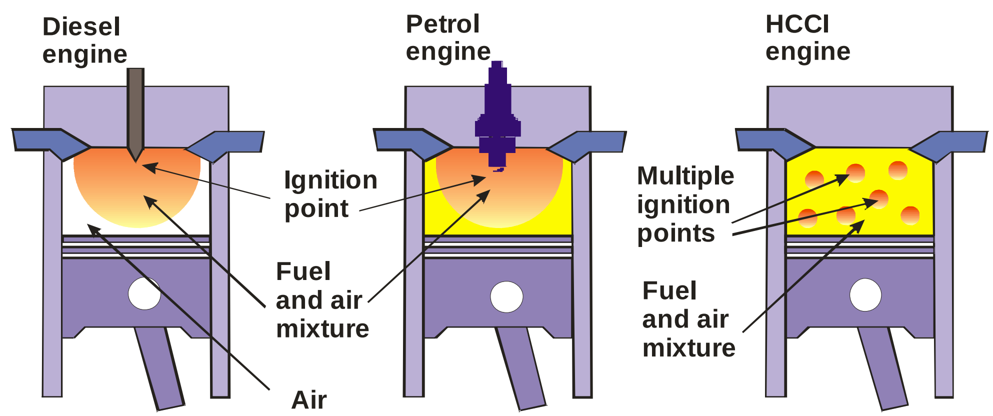
- Lean mixtures



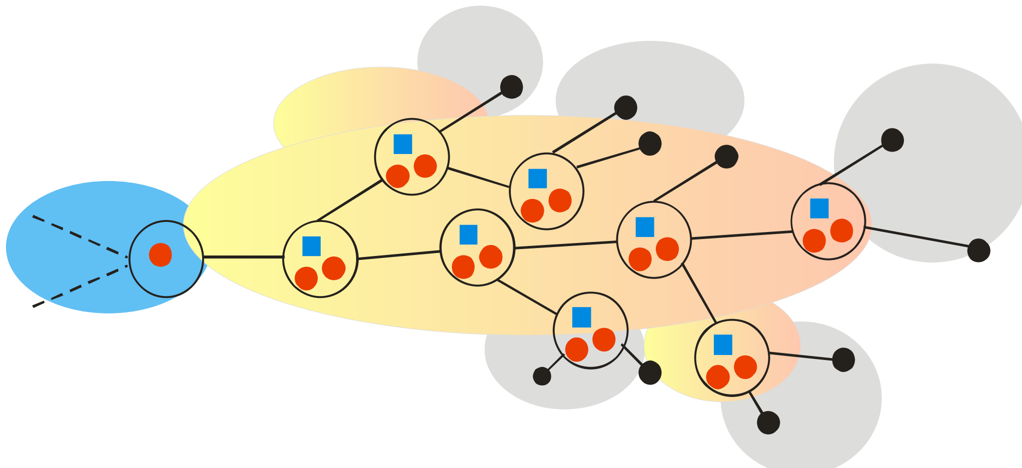
- Fast flows (1998)



- High pressures

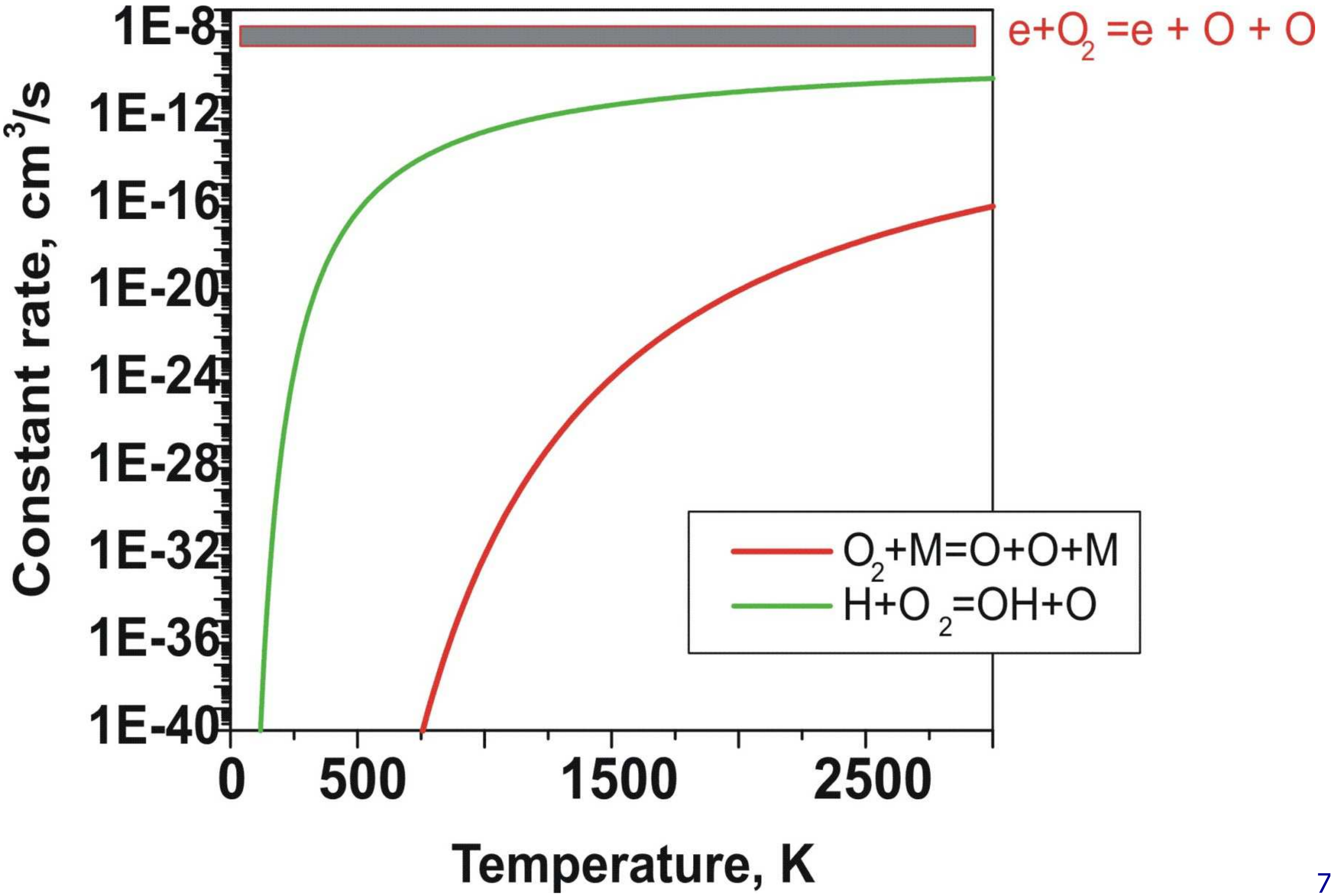


Combustion: chain reactions

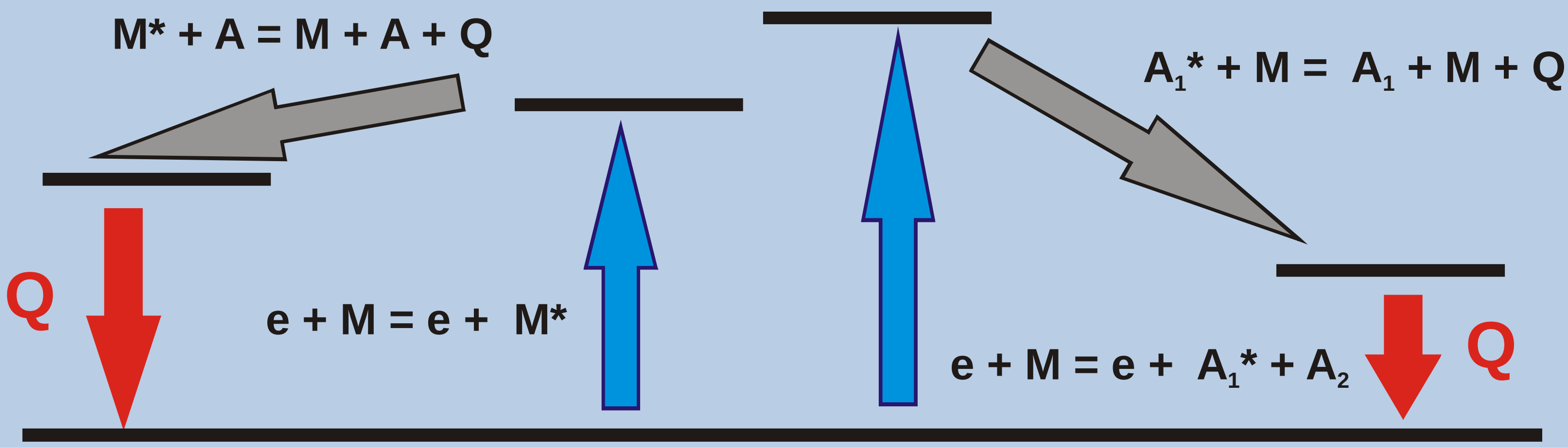


Initiation	$H_2 + O_2 = 2\ \dot{O}H + 78\ kJ$
Branching	$\dot{H} + O_2 = \dot{O}H + \dot{O} + 70\ kJ$ $\dot{O} + H_2 = \dot{O}H + \dot{H} + 8\ kJ$
Development: 2x	$\dot{O}H + H_2 = H_2O + \dot{H} - 62\ kJ$
Break	$\dot{H}$ + wall $\dot{H} + O_2 + M = H\dot{O}_2 + M - 203\ kJ$

Comparison of the reaction rates



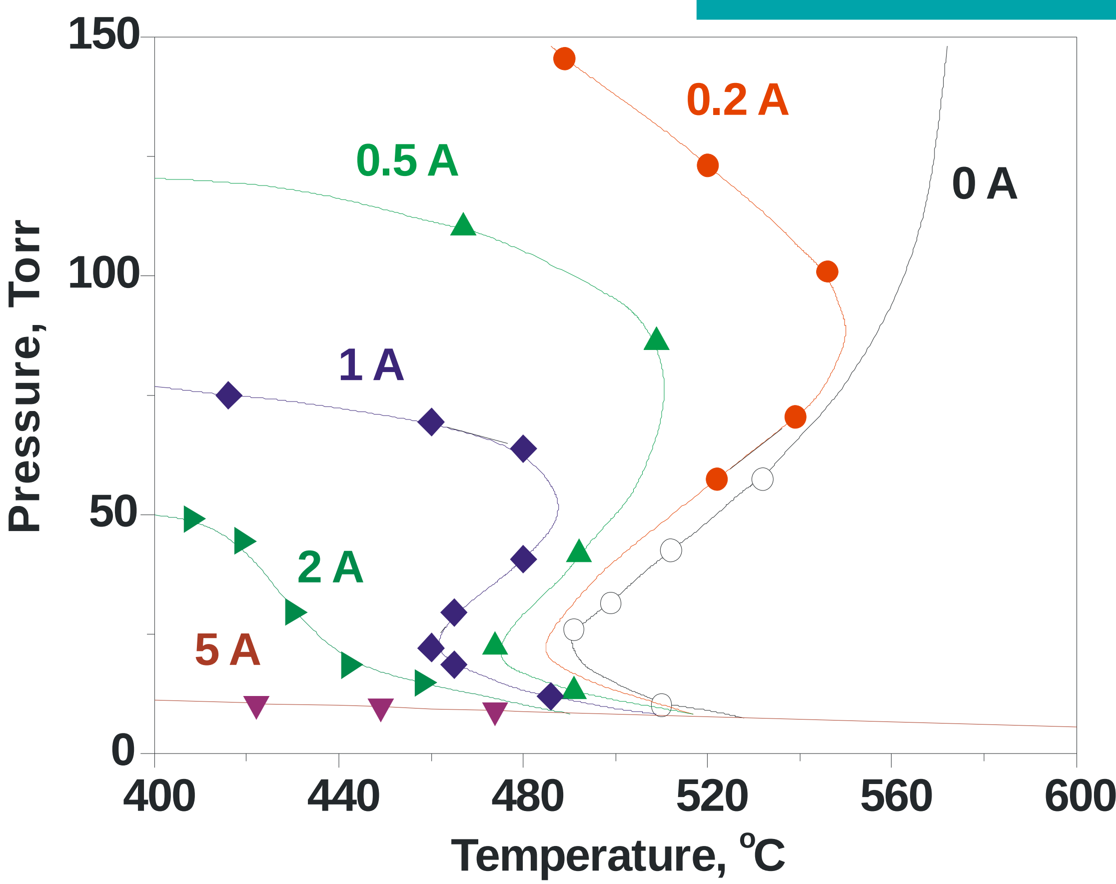
Fast gas heating: time less than VT-relaxation



$$k = BT^{n}\exp(-E_a/kT)$$

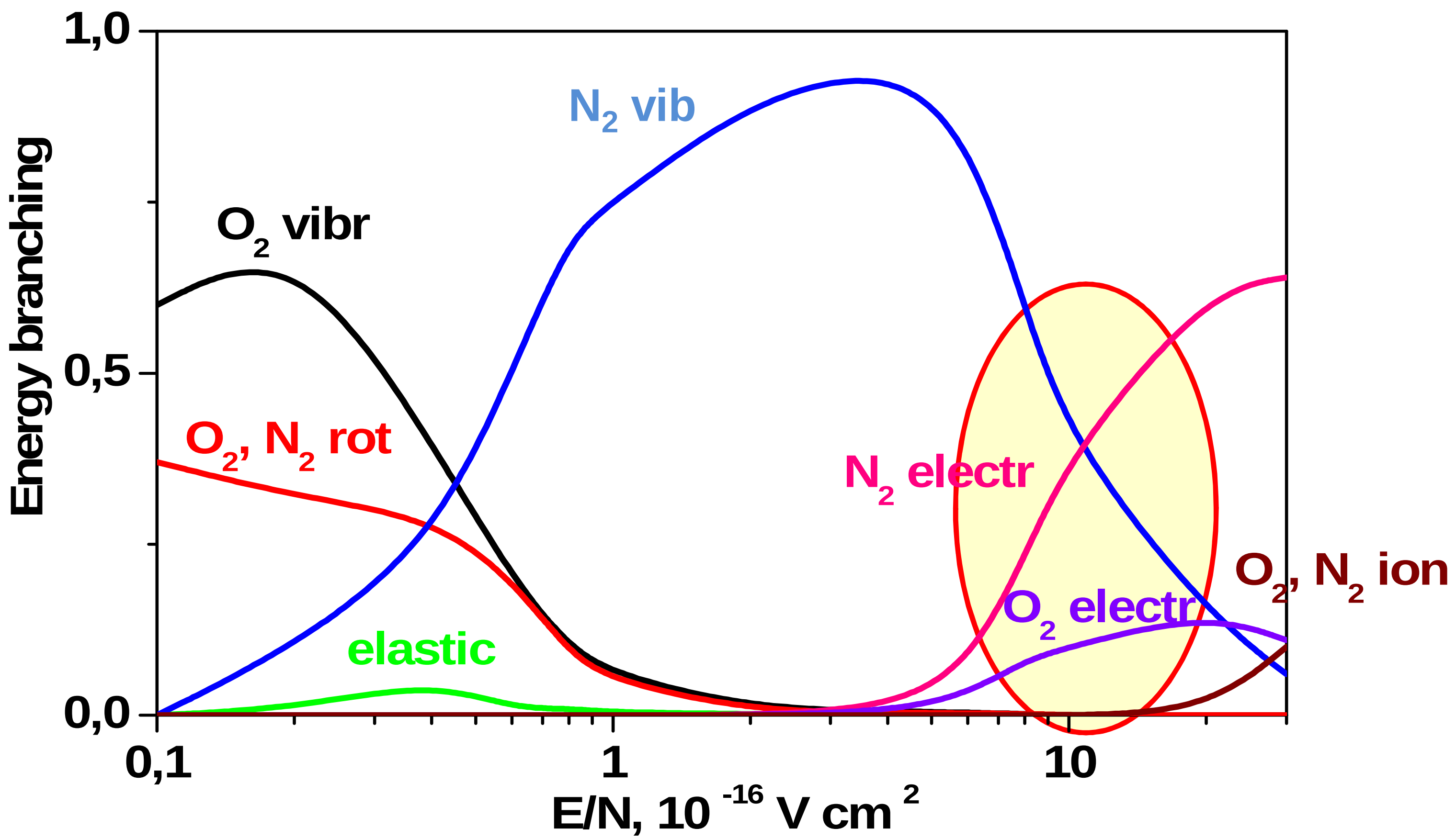
First available experiments on plasma-assited combustion

Semenov N N (1958) Some problems of chemical kinetics and reactivity *Pergamon Press*



G.Gorchakov, F.Lavrov, Influence of electric discharge on the region of spontaneous ignition in the mixture $2H_2$-O_2. Acta Physicochim. URSS (1934), 1, 139-144

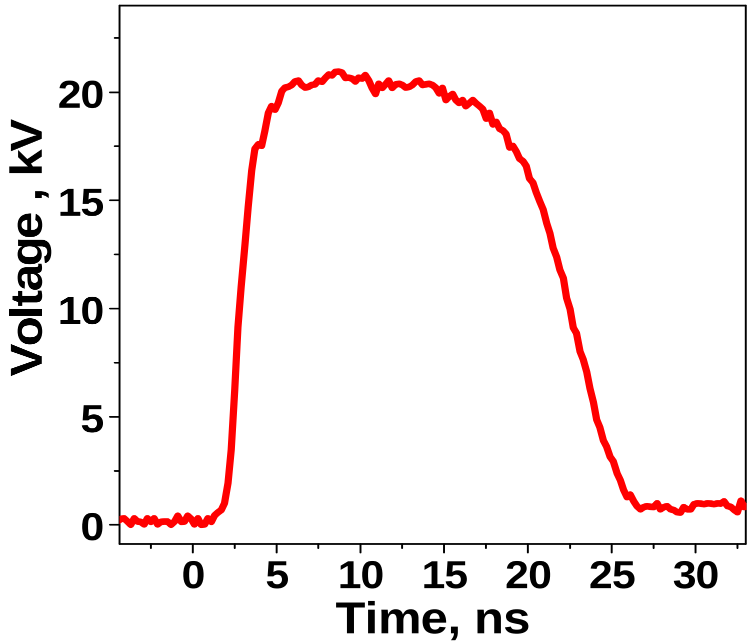
Energy branching *vs* reduced electric field *E/N*

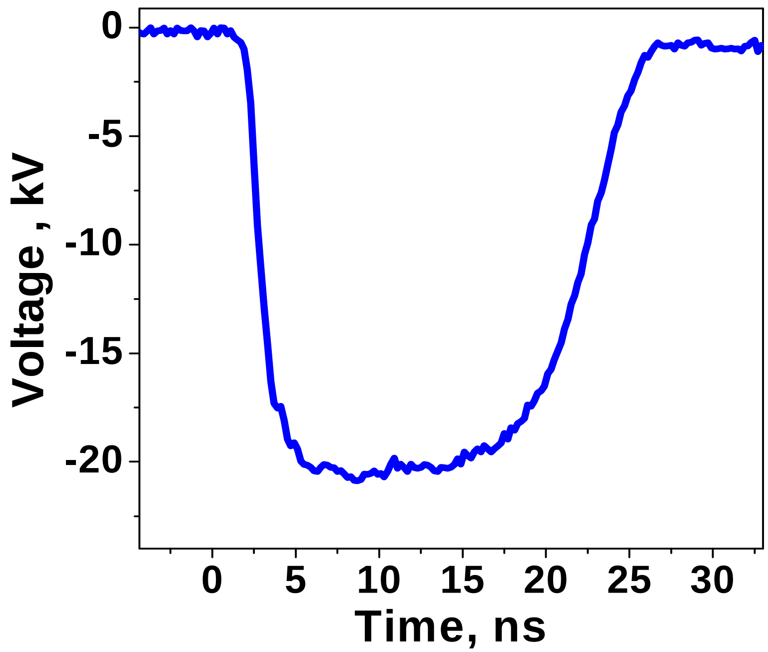


N.L. Aleksandrov, E.E. Son, 1980, in: *Plasma Chemistry,* B.M.Smirnov, ed., Atomizdat Publ., Moscow, V.7, pp. 35-75

Applied high voltage pulses

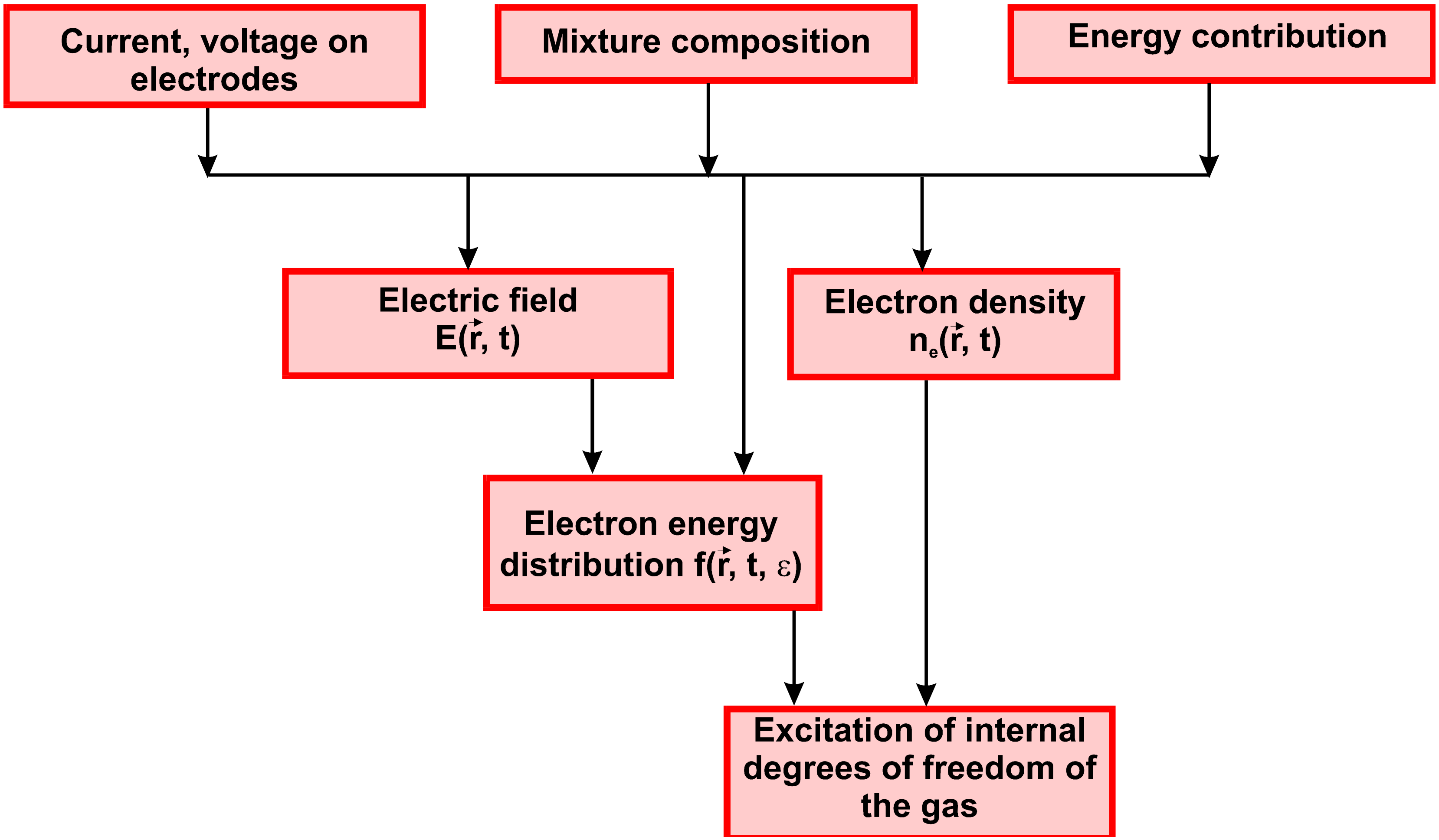
Positive and negative polarity pulses



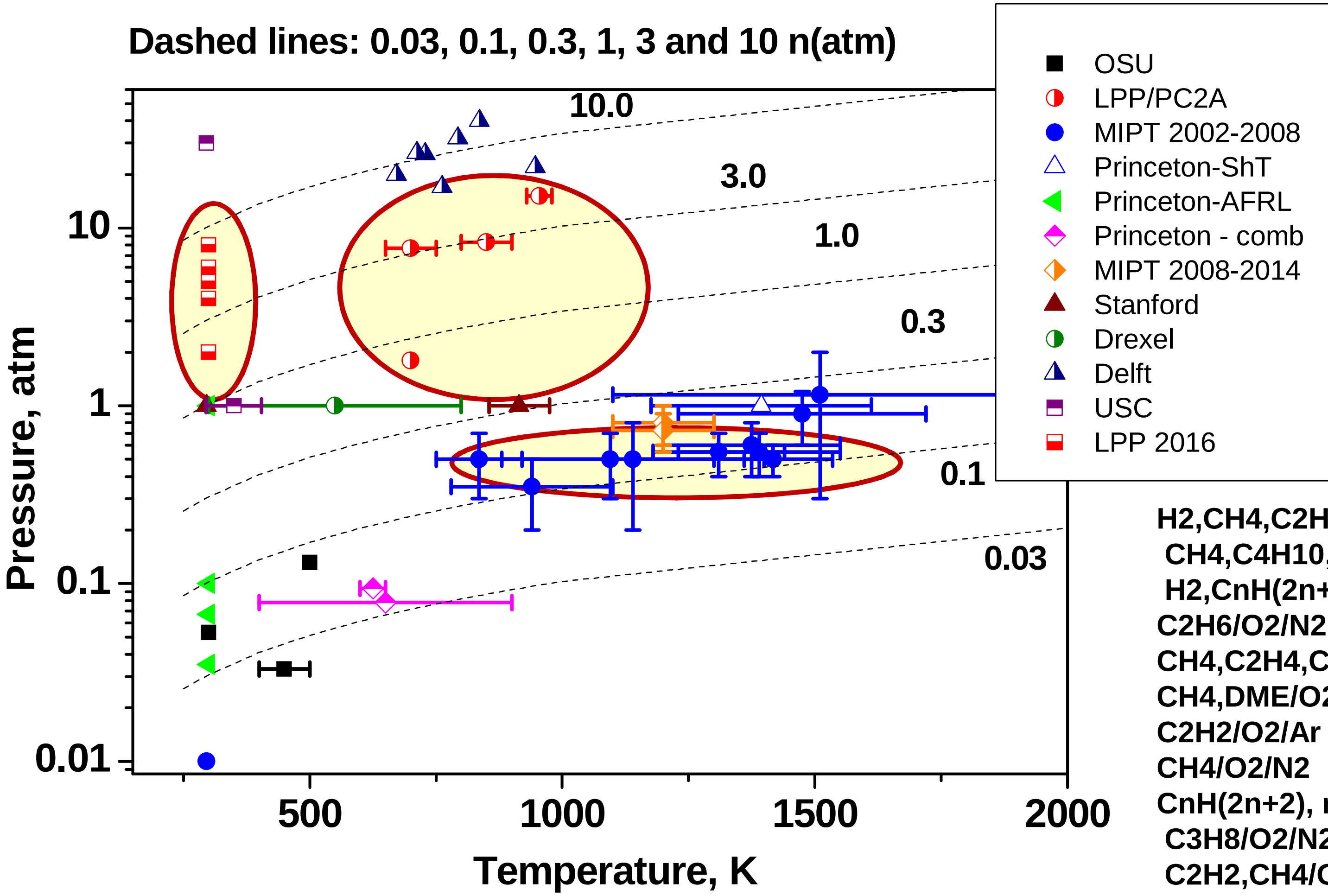


Single pulse regime, 20 ns pulse duration, 2 ns front rise time

Kinetic approach to description of a gas discharge



Field of parameters where nanosecond PAI/PAC experiments are available



H2,CH4,C2H4,C3H8/O2/N2,Ar
CH4,C4H10,C7H16/O2/N2,Ar
H2,CnH(2n+2), n=(1-10)/O2,N2O/N2,Ar,He
C2H6/O2/N2,Ar
CH4,C2H4,C3H8/O2/N2,Ar
CH4,DME/O2/He,Ar
C2H2/O2/Ar
CH4/O2/N2
CnH(2n+2), n=(1-5)/O2/N2
C3H8/O2/N2
C2H2,CH4/O2/N2

S M Starikovskaia, J. Phys. D: Appl. Phys., 47 (2014) 353001 (34pp)

All experiments were performed in a SINGLE-SHOT regime

II. Shock tube experiments: [relatively] low P and high T

Shock tube setup for plasma ignition

- Mixture composition

$CH_4/C_2H_6/C_3H_8/C_4H_{10}/C_5H_{12}$ - O_2 – Ar (90%)

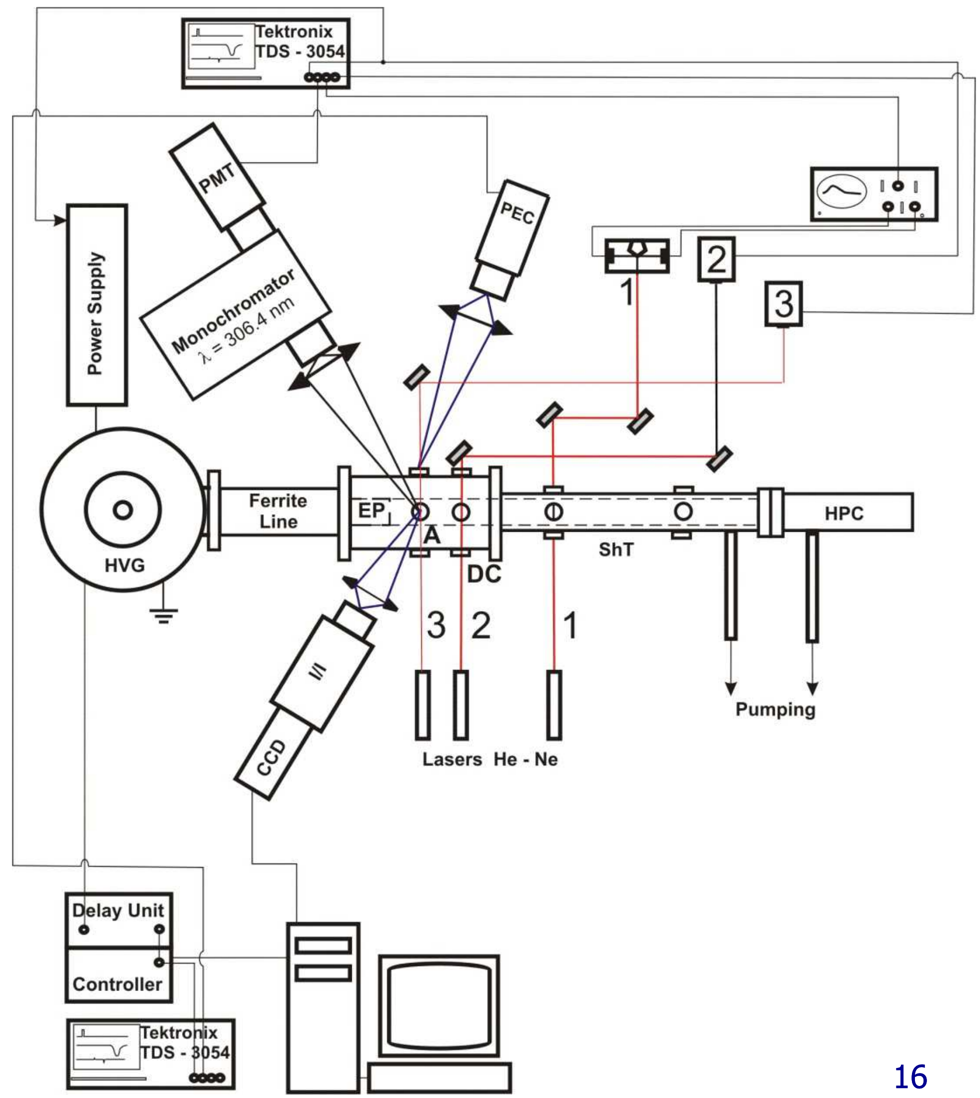
- Temperature

950-2000 K

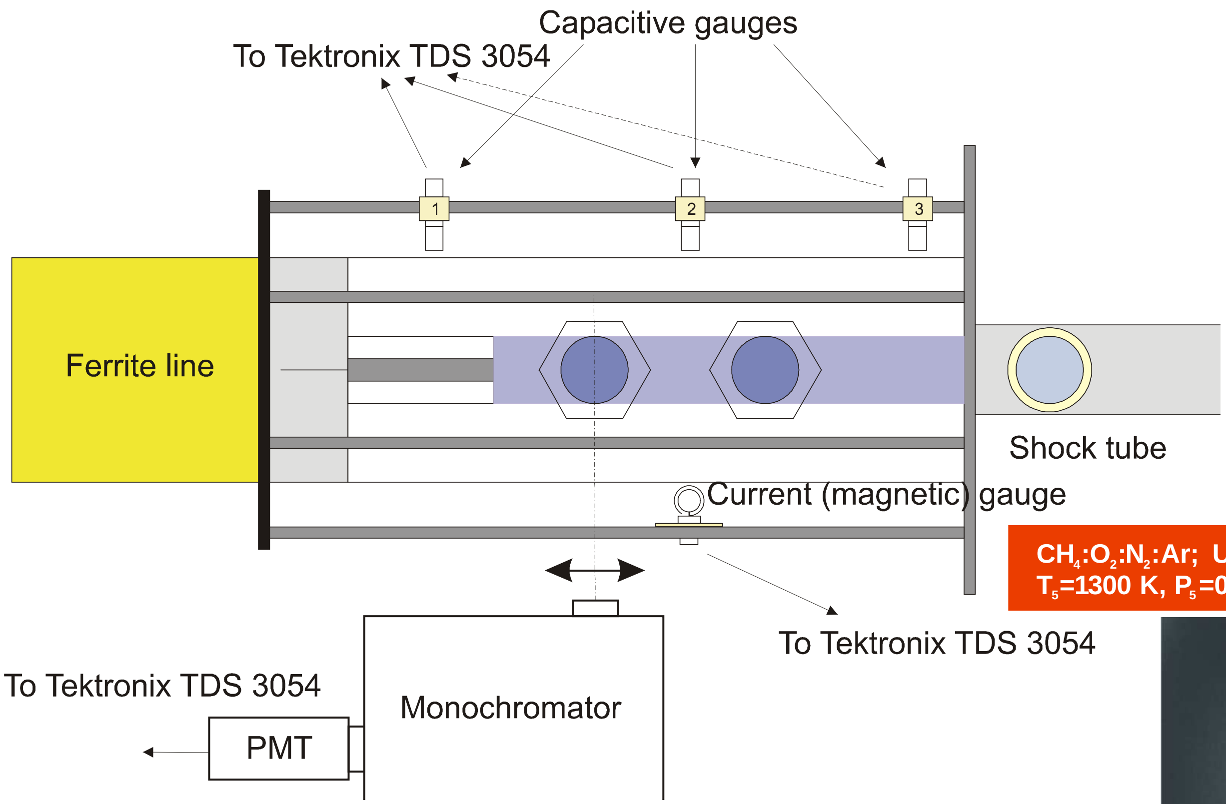
- Pressure

0.2-1.0 atm

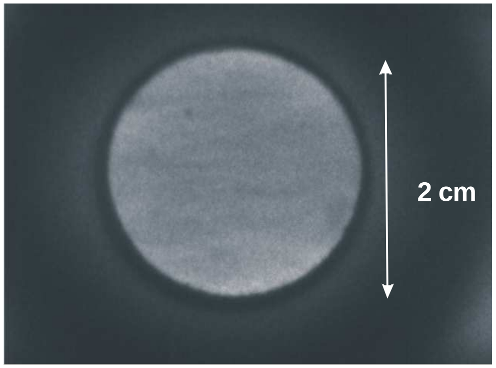
- T_5, P_5
- T_{ign}
- E/N, I, W



Dielectric section of a shock tube

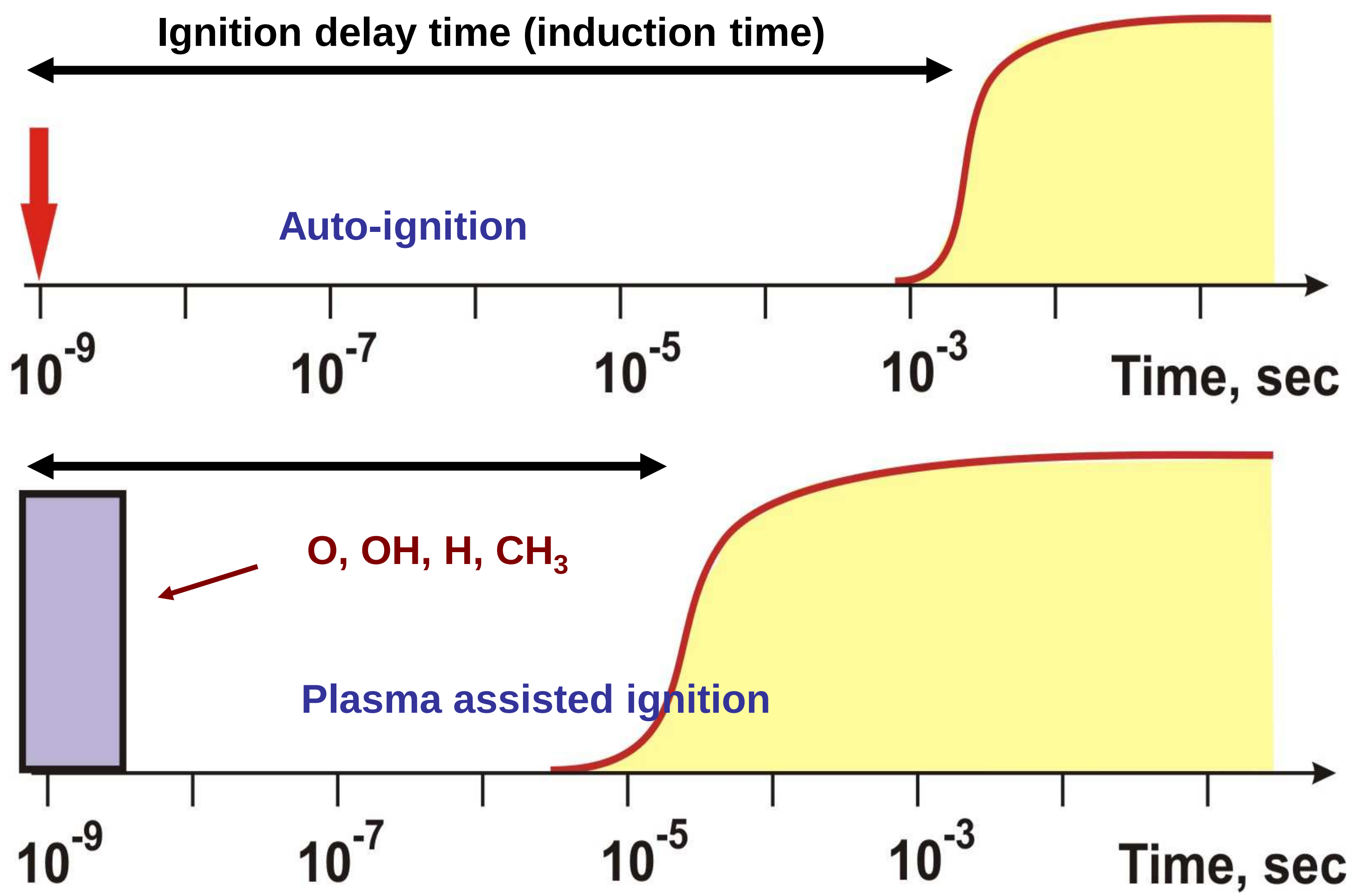


$CH_4:O_2:N_2:Ar$; U=-110 kV
T_5=1300 K, P_5=0.5 atm

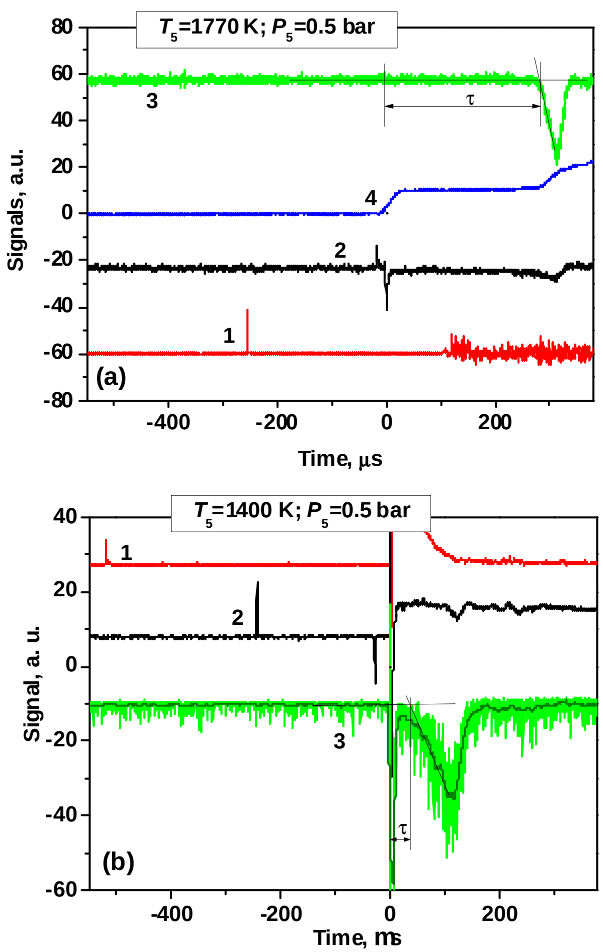


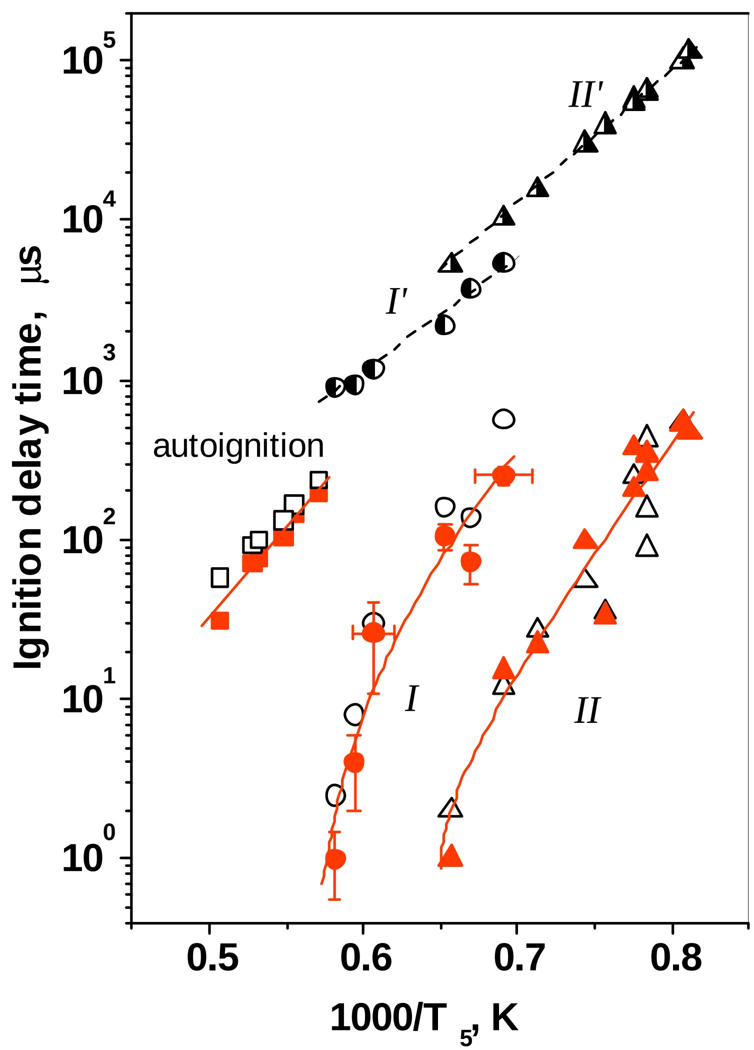
Starikovskaia S M, Kukaev E N, Kuksin A Yu, Nudnova M M and Starikovskii
Comb. and Flame, 2004, 139, 177-87

The idea of the experiment



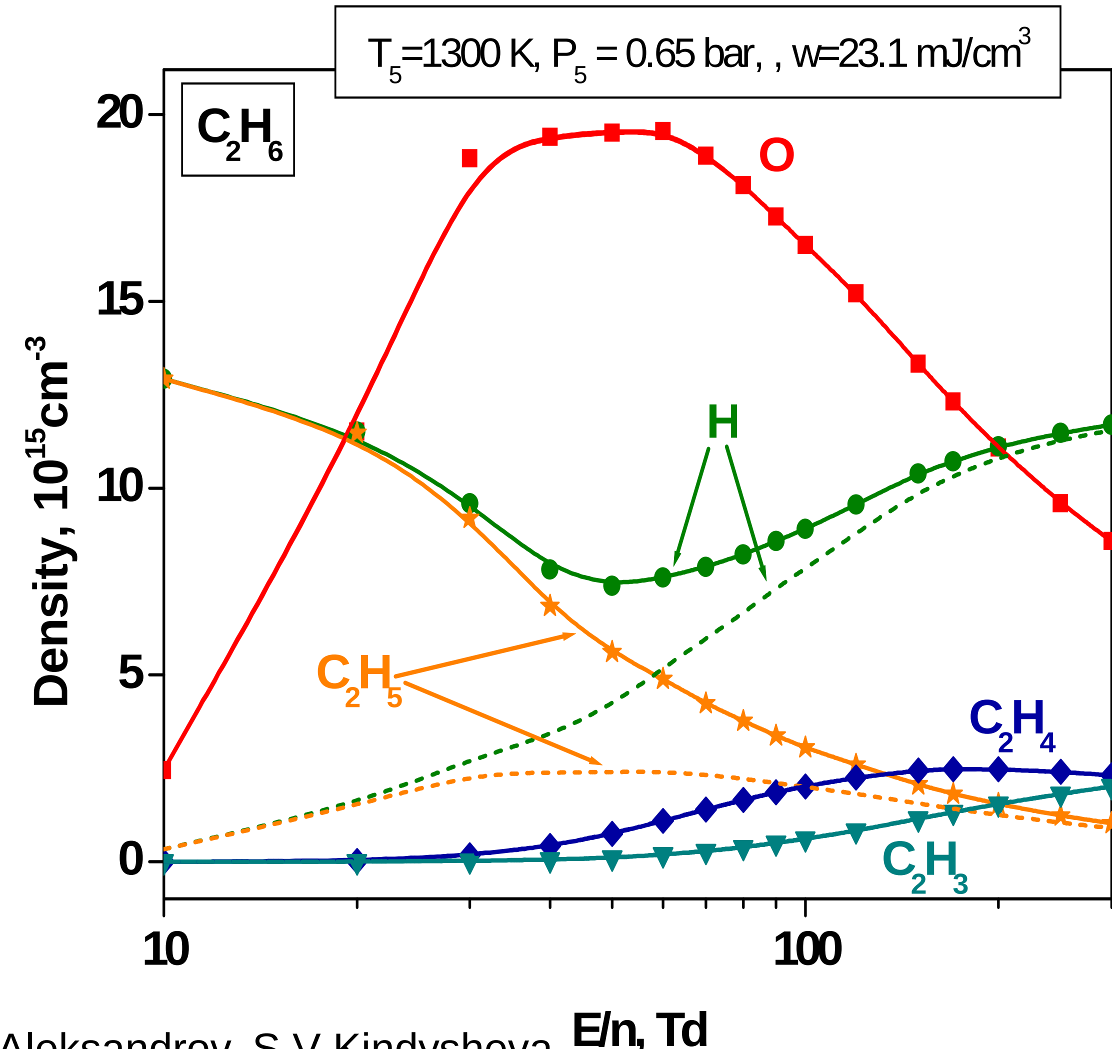
Shift of the ignition delay time: $(CH_4:O_2):Ar$ = 90:10 mixture





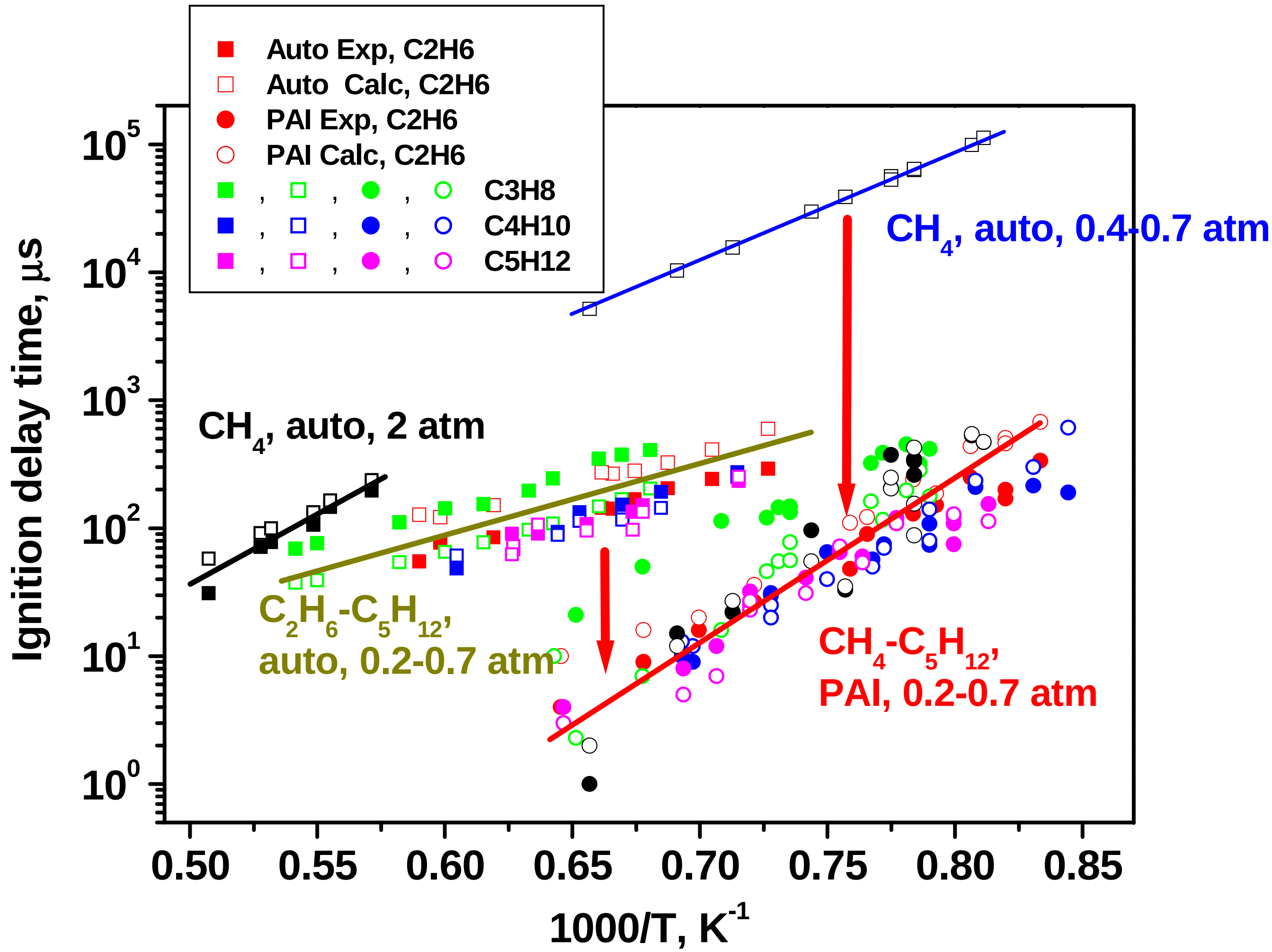
I N Kosarev, N L Aleksandrov, S V Kindysheva,
S M Starikovskaia, A Yu Starikovskii, *Comb Flame,* 154 (2008) 569-586

Dissociation in a nanosecond discharge $(C_2H_6:O_2)$:Ar, Hayashi (C_2H_6), Braginsky (O_2), Tachibana (Ar)



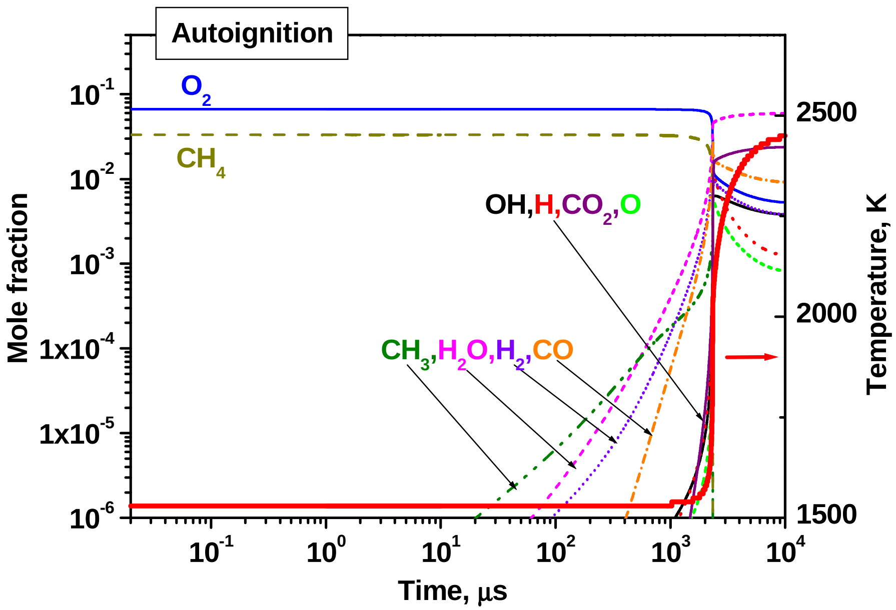
I N Kosarev, N L Aleksandrov, S V Kindysheva,
S M Starikovskaia, A Yu Starikovskii, *Comb Flame,* 156 (2009) 221-233

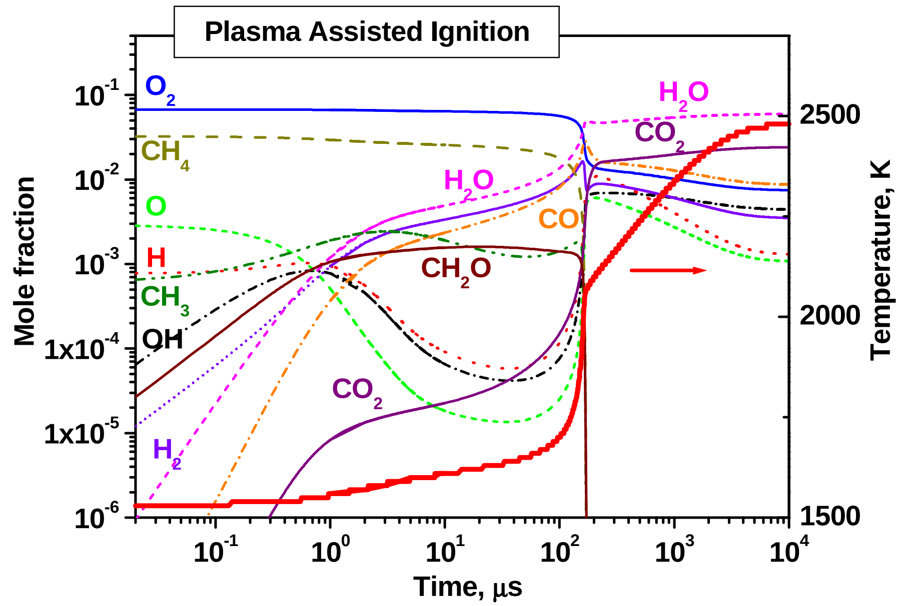
Decrease of ignition delay time: moderate gas densities; uniform ns discharge



N L Aleksandrov, S V Kindysheva, I N Kosarev, S M Starikovskaia, A Yu Starikovskii, *Proc. of Combustion Institute,* 32 (2009) 205-212

Kinetics of the ignition: kinetic curves (T_5=1530 K, n_5=5x10^{18} cm^{-3})





Plasma assisted ignition is characterized by:

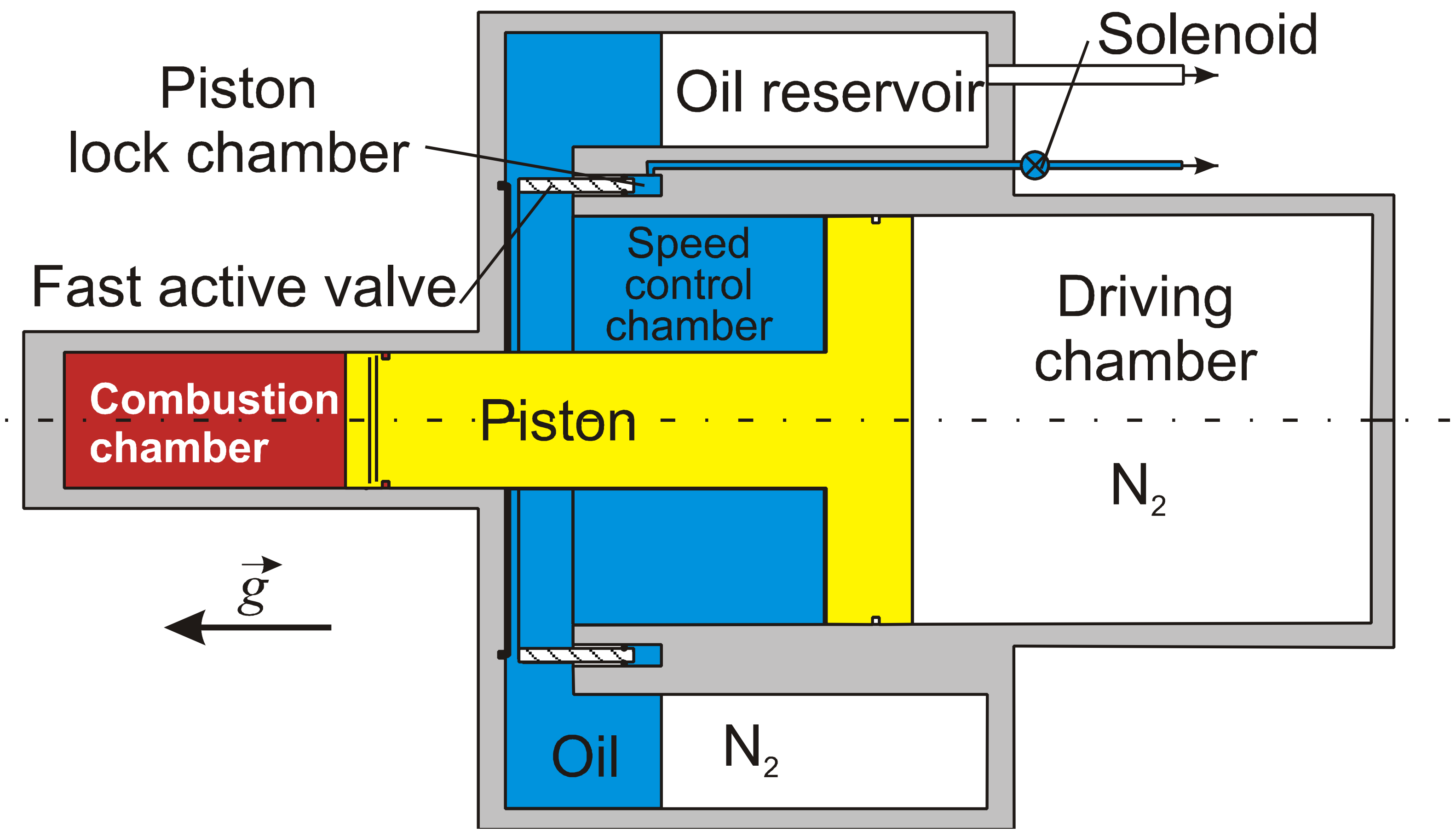
- slow increase of gas temperature
- developed kinetics of intermediates
- partial fuel conversion during induction time

N L Aleksandrov, S V Kindysheva, I N Kosarev, S M Starikovskaia, A Yu Starikovskii, *Proc. of Combustion Institute,* 32 (2009) 205-212

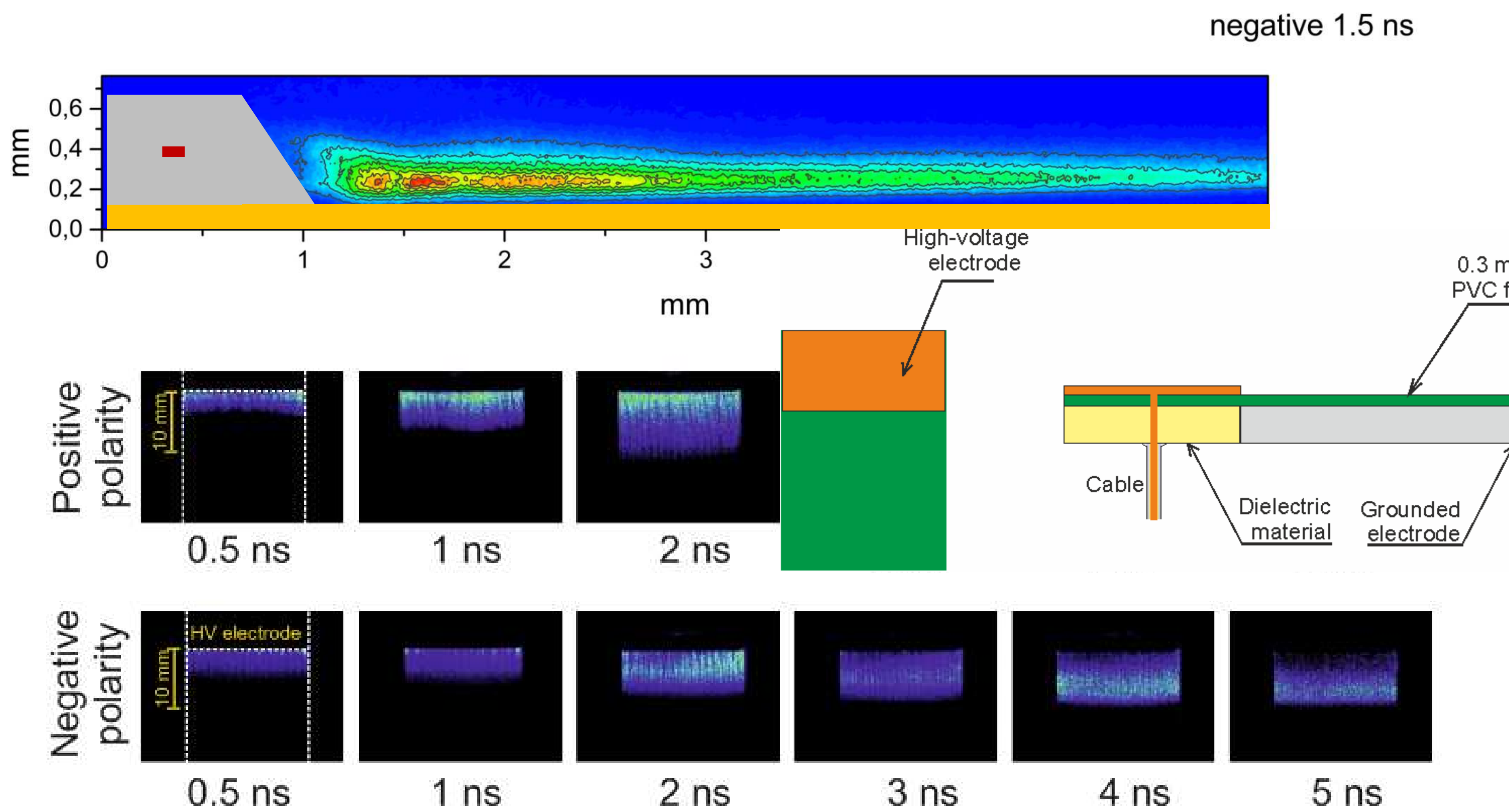
II. Rapid compression machine (RCM) experiments: high P and [relatively] low T

Rapid compression machine (RCM)

P.Park and J.C.Keck, SAE Paper 900027



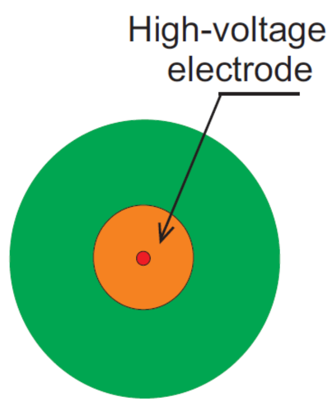
Nanosecond surface dielectric barrier discharge (nSDBD, for flow control)

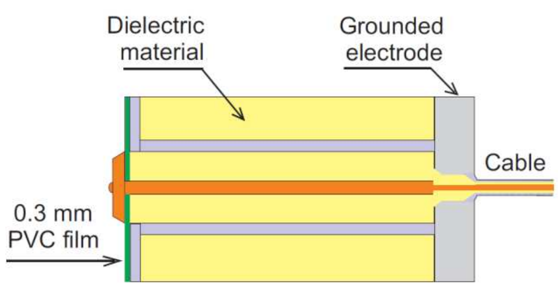


Y Zhu, S Shcherbanev, B.Baron and S. Starikovskaia
PSST, 26 (2017) 125004

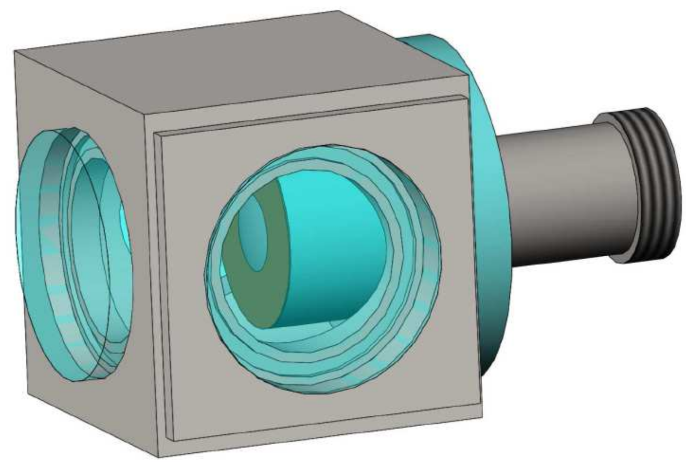
Cylindrical electrode system (for PAC)

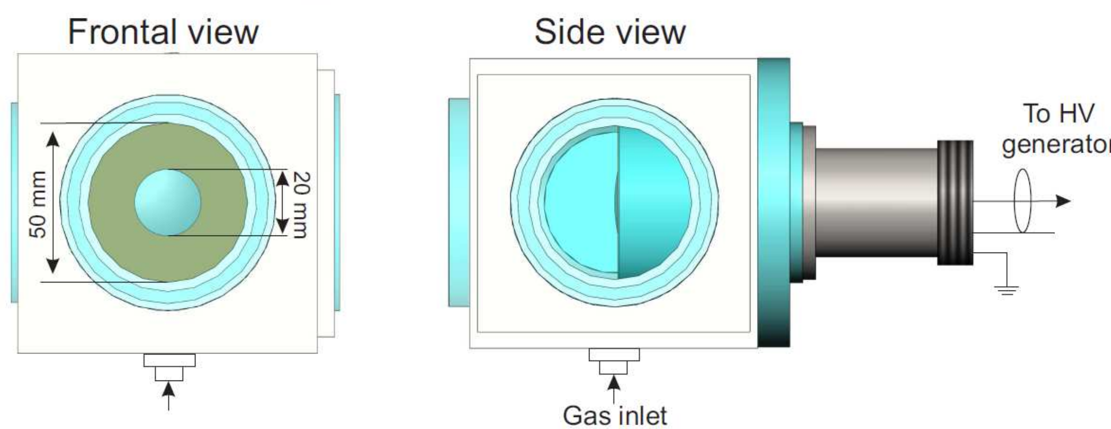
Electrode configuration





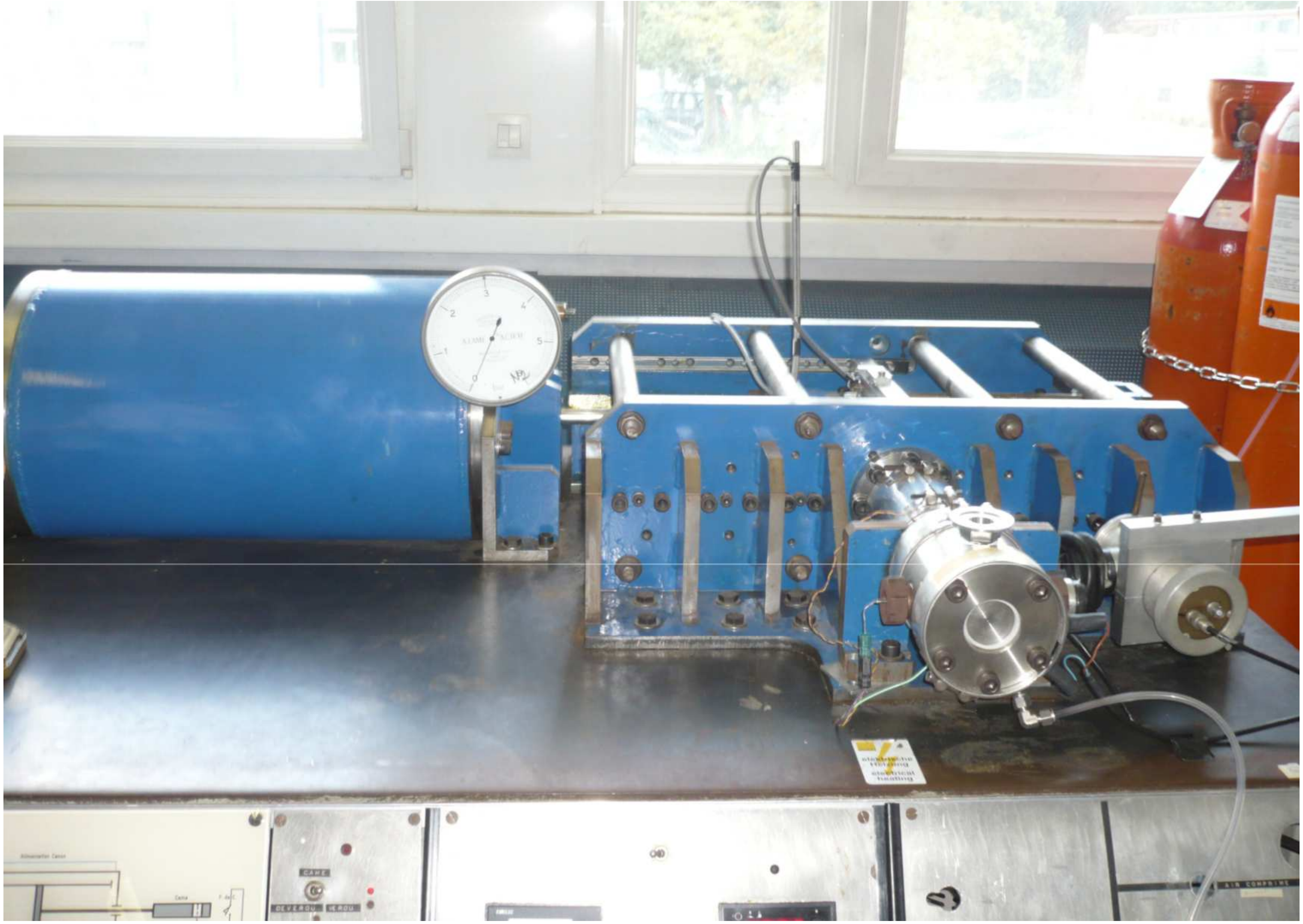
Cubic HP chamber





HV electrode,
2 cm in diameter

Rapid compression machine (RCM), Lille



Mixtures used in experiments:

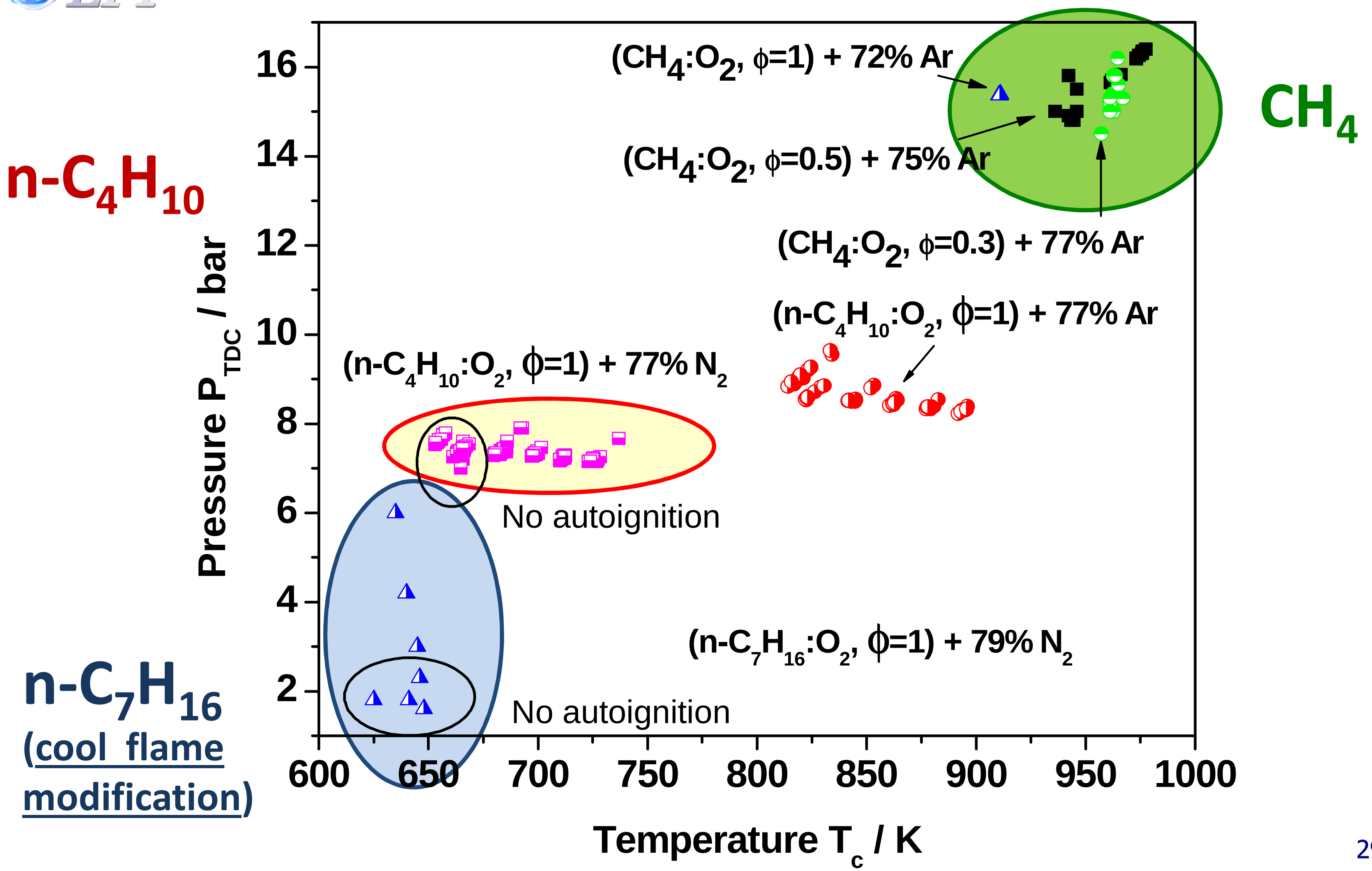
1) $CH_4/O_2/Ar$, $\phi=1, 0.5, 0.3$, 70-75 % of Ar

2) $n\text{-}C_4H_{10}/O_2/Ar/N_2$, $\phi=1$, 38 % of N_2, 38 % of Ar

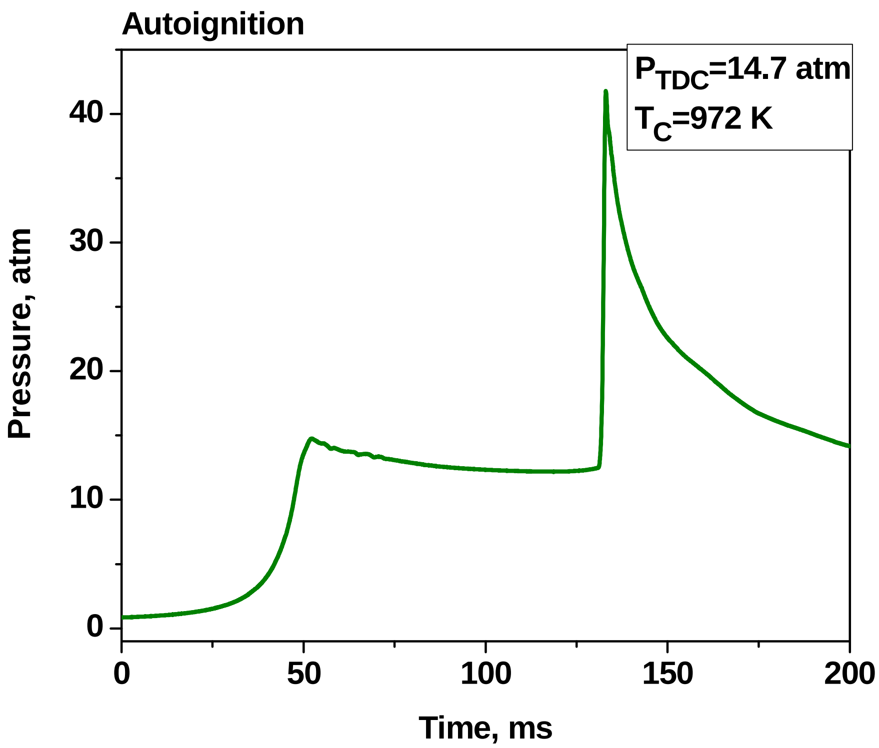
3) $n\text{-}C_4H_{10}/O_2/Ar$, $\phi=1$, 76 % of Ar

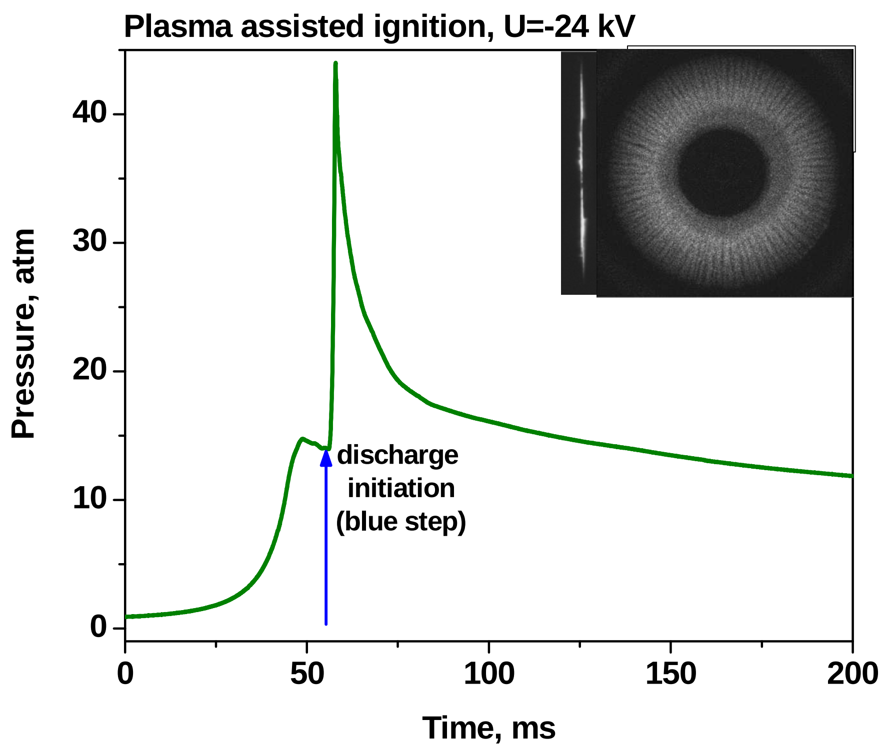
4) $n\text{-}C_4H_{10}/O_2/N_2$, $\phi=1$, 76 % of N_2

P-T diagram for RCM experiments



Autoignition *vs* plasma ignition in RCM at P_{TDC}=15 bar and T_C=970 K, $(CH_4:O_2)$+76%Ar

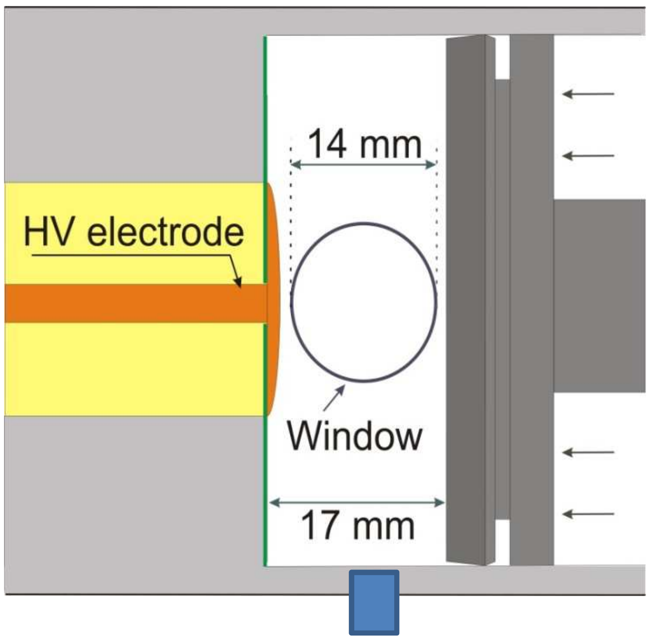




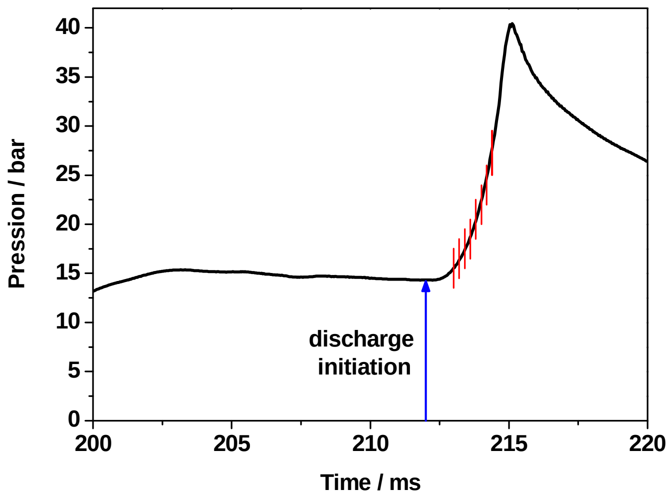
S.A. Stepanyan, M.A. Boumehdi, G. Vanhove, P. Desgroux, S.M. Starikovskaia, N.A. Popov, Comb. Flame, 162 (2015) 1336-1349

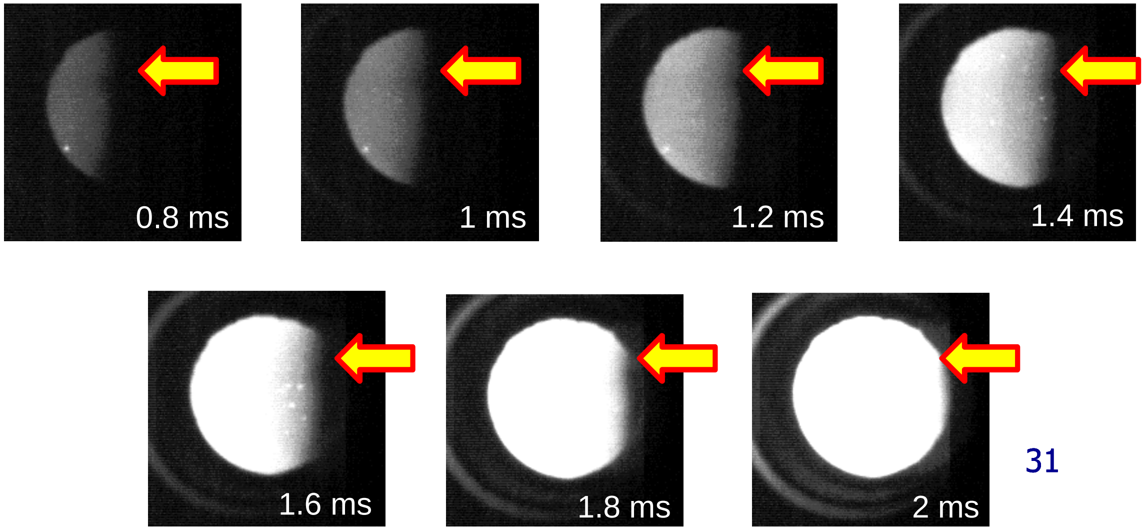
Pressure trace and corresponding fast imaging of flame propagation

S.A. Stepanyan, M.A. Boumehdi, G. Vanhove, P. Desgroux, S.M. Starikovskaia, N.A. Popov, Comb. Flame, 162 (2015) 1336-1349



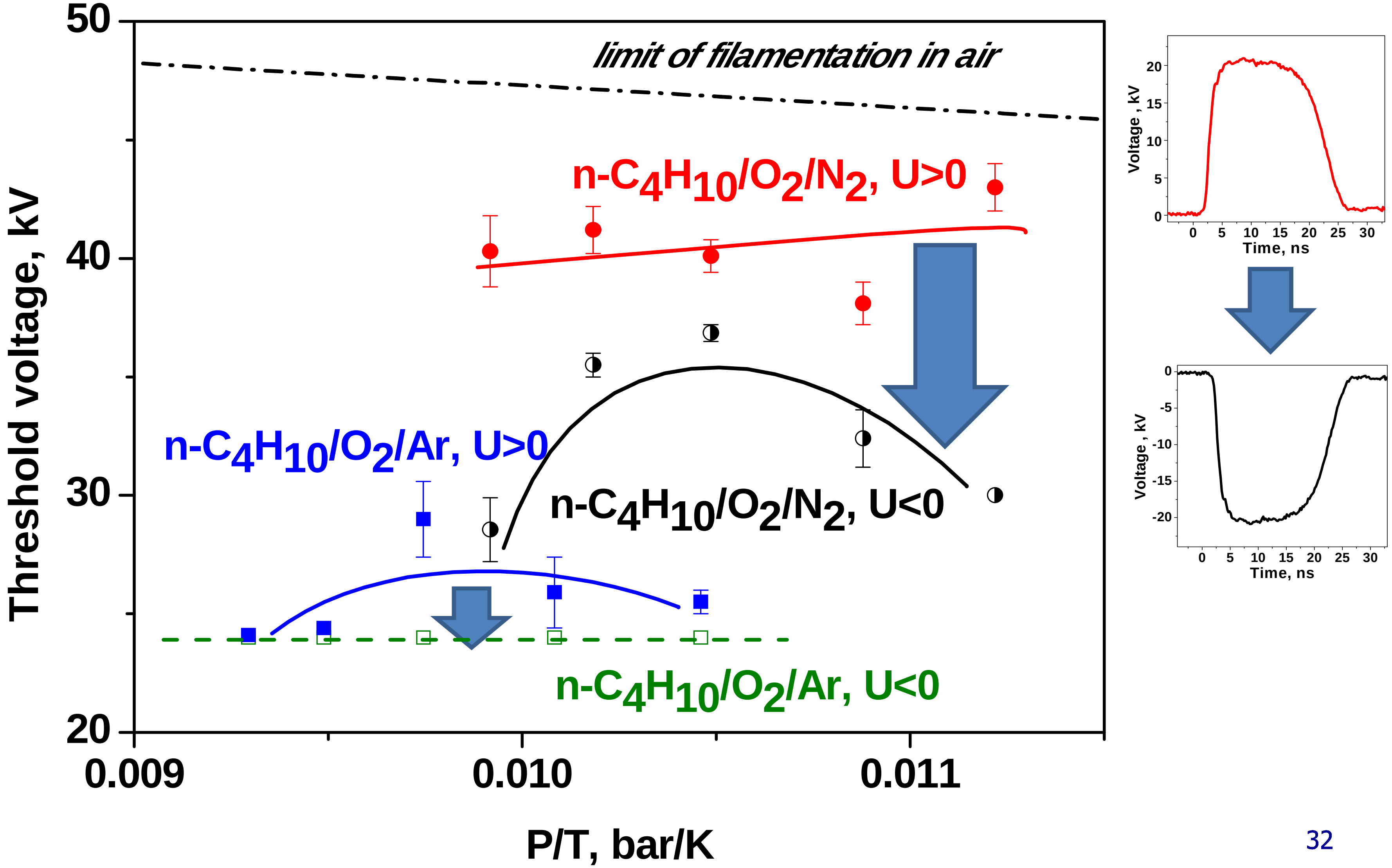
Pressure detector





CH_4:O_2, ER=1 + 70% Ar,
T_C=947 K, P_{TDC}=15.4 bar

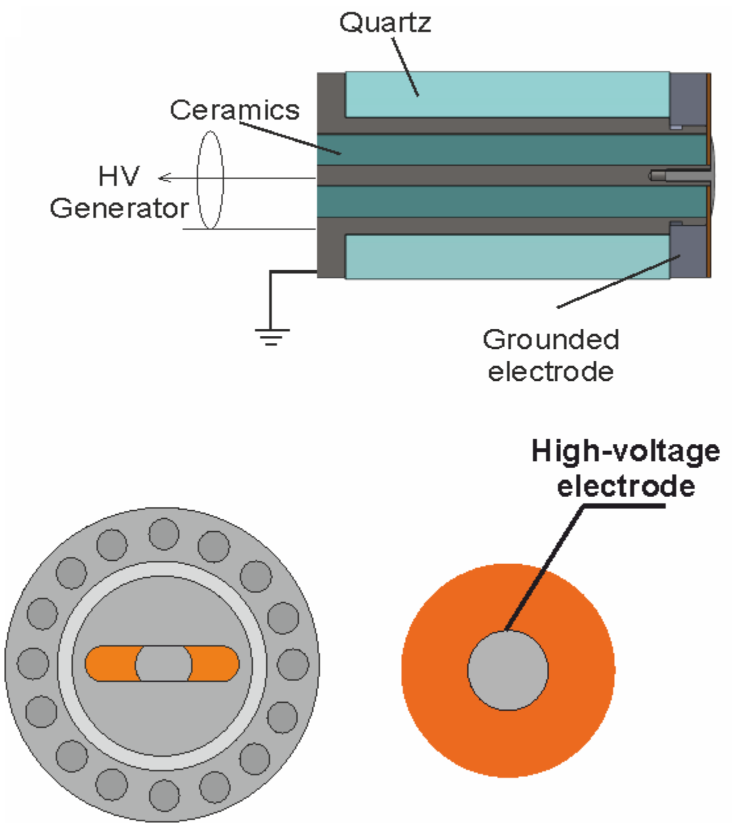
Ignition threshold and polarity of the high-voltage pulse



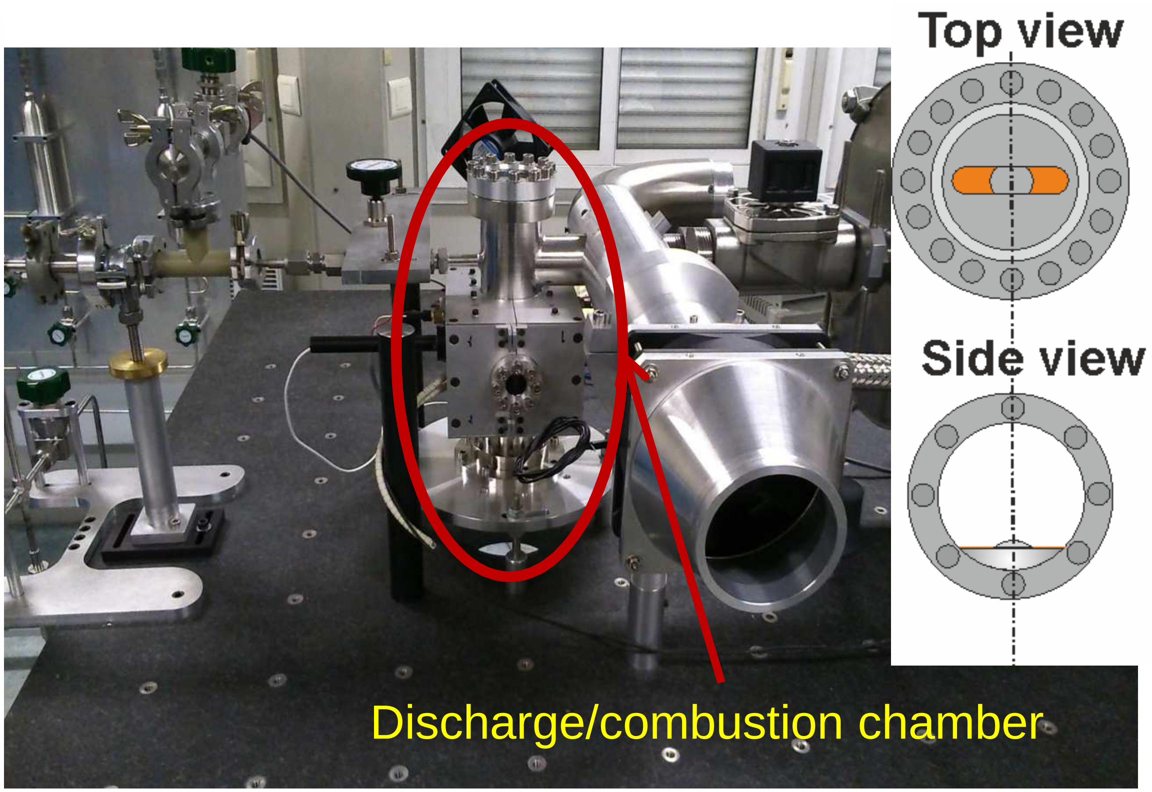
III. High pressure high temperature (HPHT) chamber experiments: high P and low T [T=300 K]

High-Pressure and High-Temperature (HPHT) discharge/combustion chamber

Electrode configuration

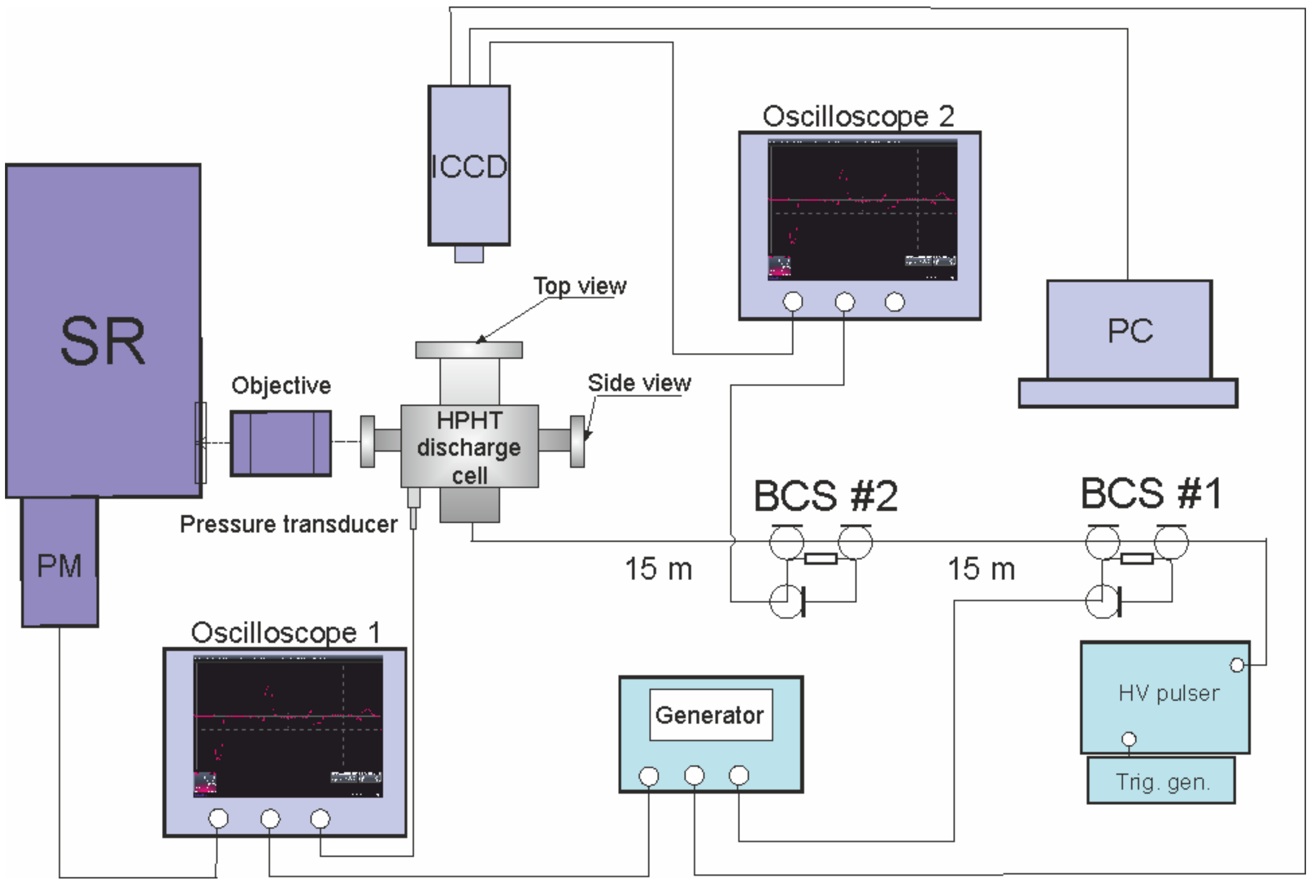


General view of the HPHT setup



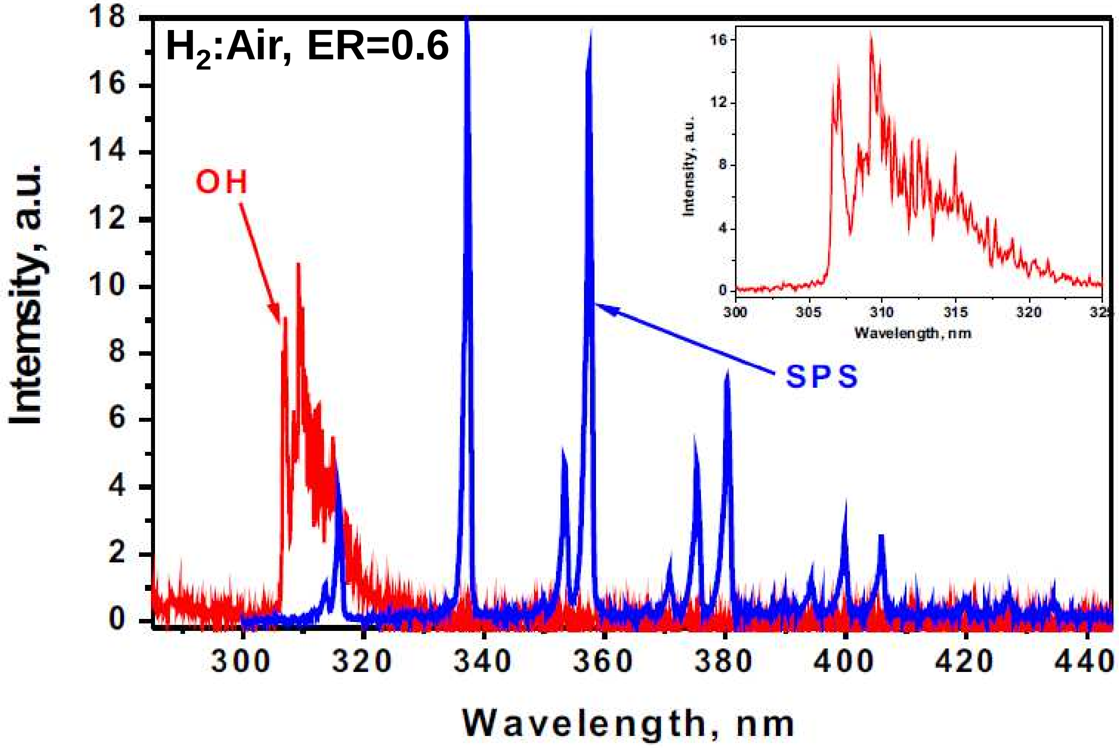
Experimental setup

The scheme of experimental setup. SR – Spectrograph, ICCD – camera, PC – computer, BCS – back current shunt,

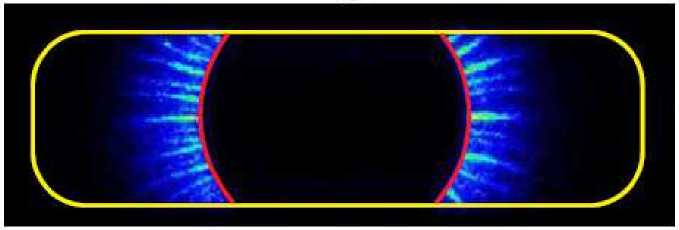


nSDBD and Flame Initiation, P=3 bar, U=-50 kV

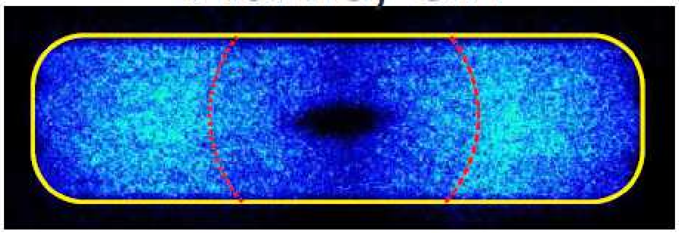
Discharge (ns) and combustion (ms) emission patterns



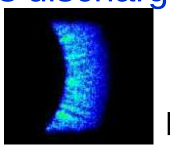
Discharge, SPS



Flame, OH

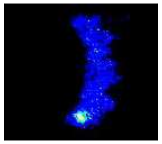


ns discharge



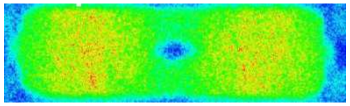
$N_2(v)$, N_2(A,B,C,…), H, O(^{1}D), $O_2(a^1\Delta_g)$, *etc.*

Intermediate chemistry



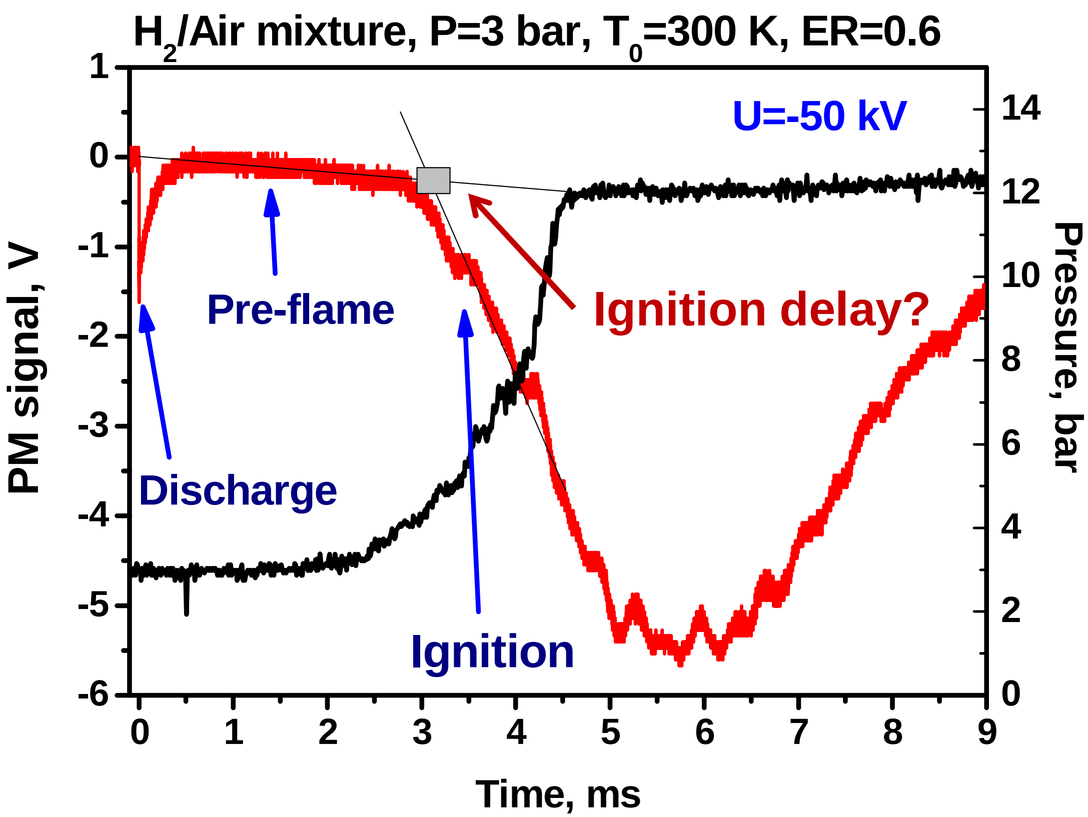
O, OH, H, HO_2, H_2O_2, H_2O, *etc.*

Flame propagation, Combustion



time

Initiation of Combustion with nSDBD



- Yes, for combustion!
- No, for plasma chemistry

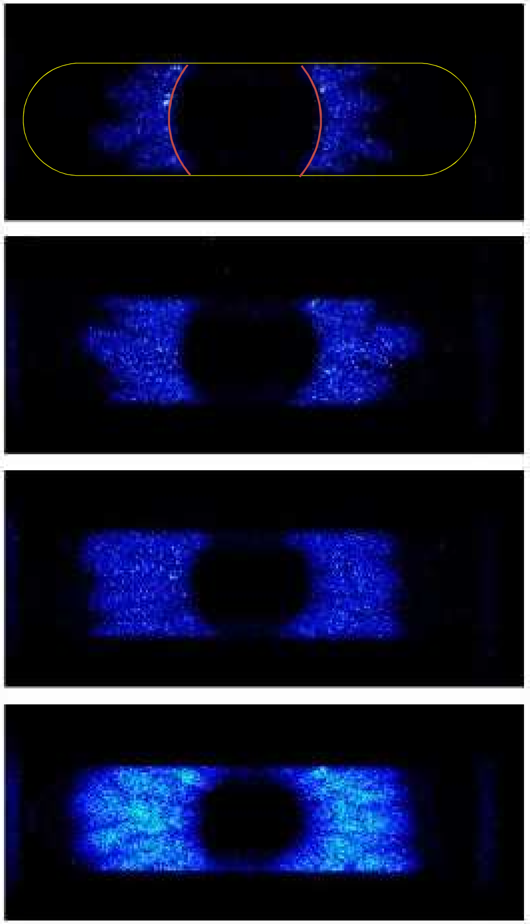
Delay: | **ICCD gate: 50 μs**

50 μs

100 μs

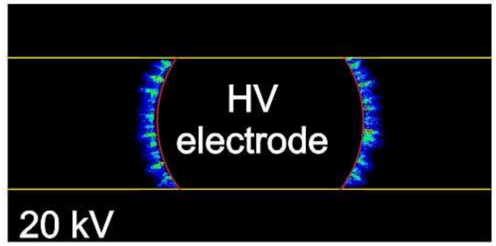
200 μs

400 μs



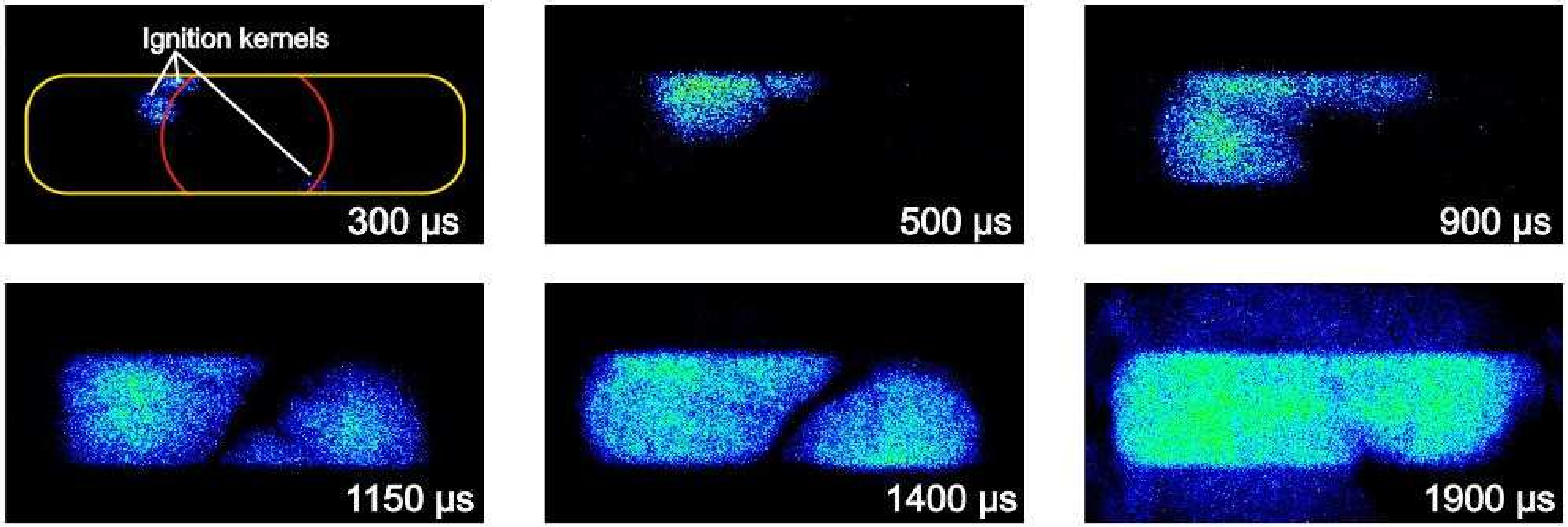
Flame Initiation in H_2/Air ER=0.5, P=6 bar

<u>First regime of ignition:</u>
Ignition kernels



Polarity: U>0

Energy deposition
W= 3 mJ

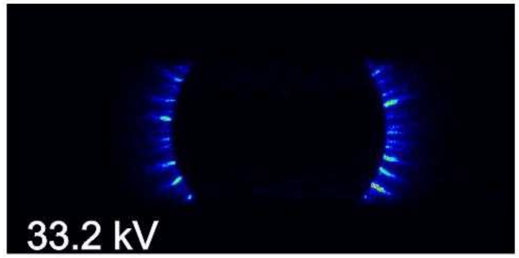


Ignition with a few ignition kernels near HV electrode. Streamer discharge.
Pressure 6 bar, Temperature 300 K.

Flame Initiation in H_2/Air ER=0.5, P=6 bar

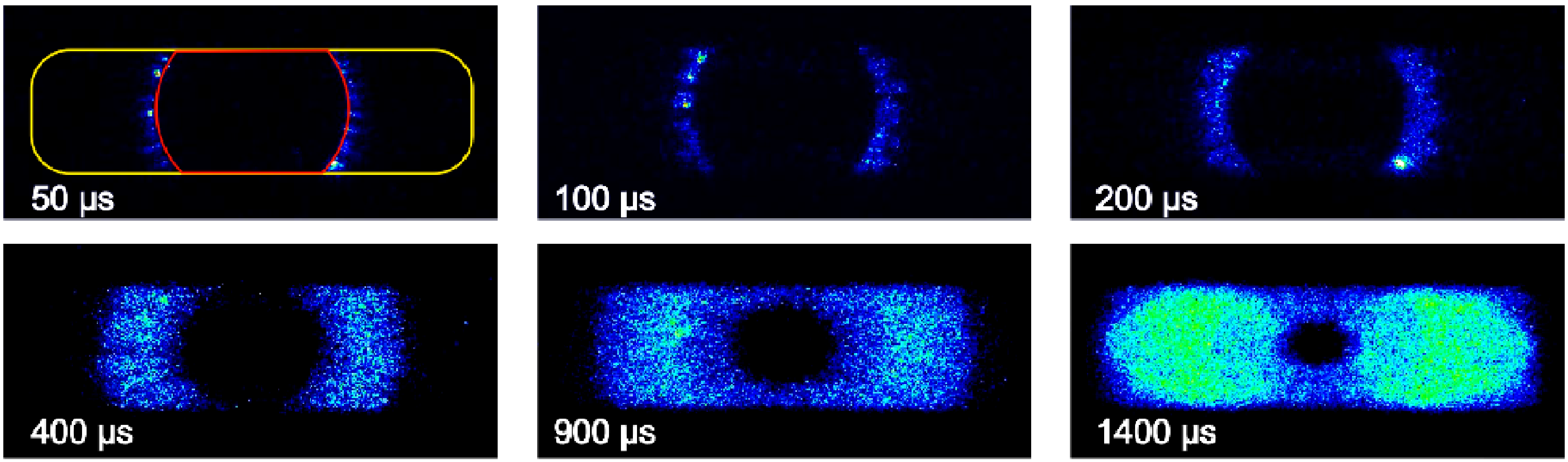
Second regime of ignition:

Ignition along the perimeter of HV electrode



Polarity: U>0

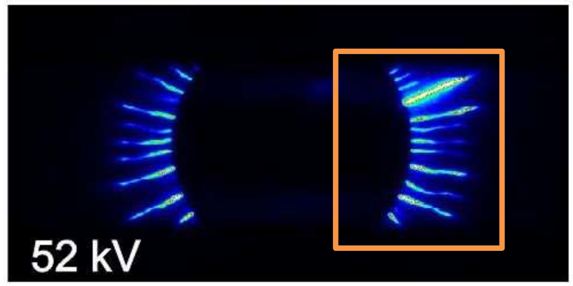
Energy deposition W= 4.8 mJ



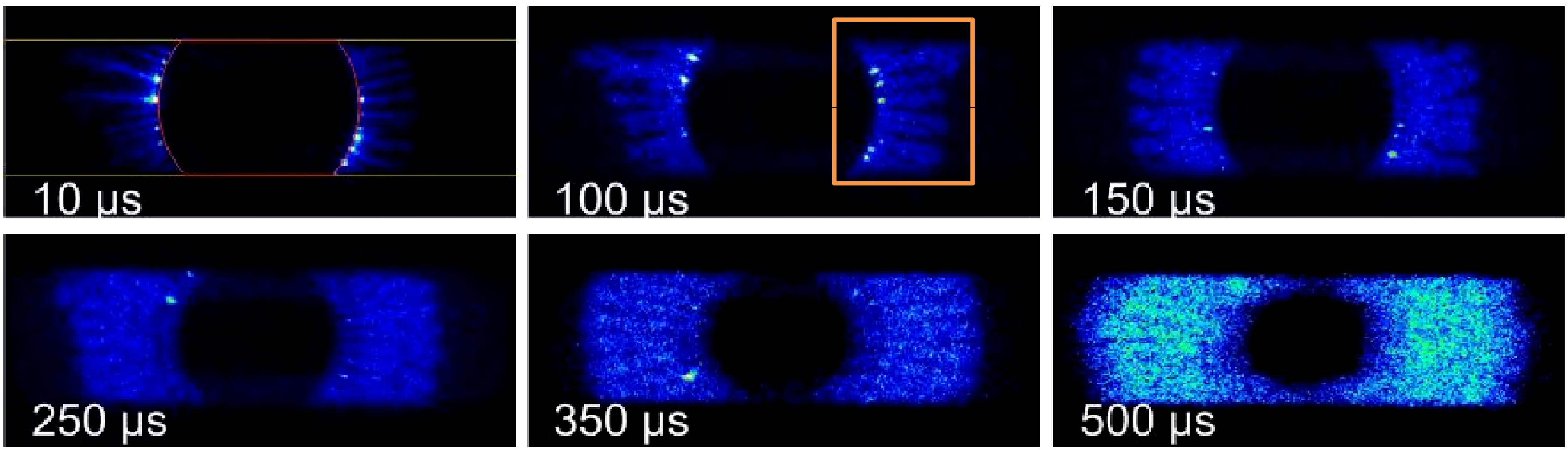
Quasiuniform ignition around HV electrode. Streamer discharge.
Pressure 6 bar, Temperature 300 K.

Flame Initiation in H_2/Air ER=0.5, P=6 bar

<u>Third regime of ignition:</u>
Ignition along the discharge channels



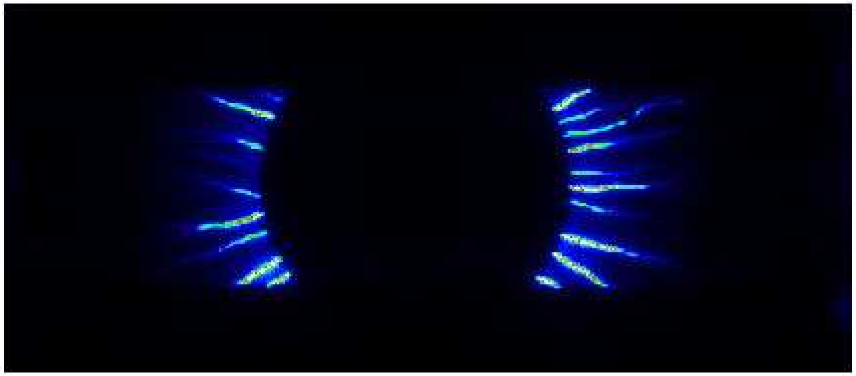
Polarity: U>0
Energy deposition W= 12 mJ



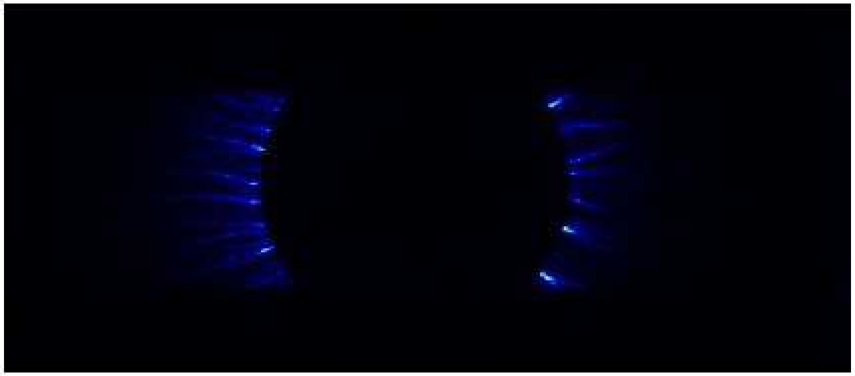
Ignition along the channels. Filamentary discharge.
Pressure 6 bar, Temperature 300 K.

Discharges in different gas mixtures

Discharge in methane/O_2/Ar



Discharge in n-heptane/O_2/Ar

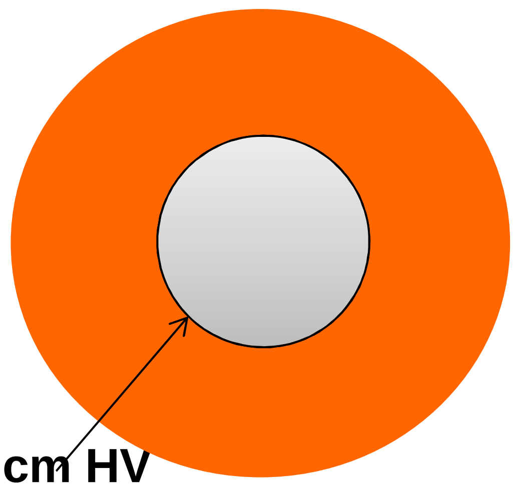


Discharges in $CH_4/O_2/Ar$ (ER=0.6) and
n-$C_7H_{16}/O_2/Ar$ (ER=1) mixtures,
P_0=3 bar, T_0=300 K, voltage on the electrode U=+38 kV

IV. High pressure surface DBD discharge: streamer-to-filament transition

Two modes of nSDBD (velocity is a few mm/ns)

Electrode system

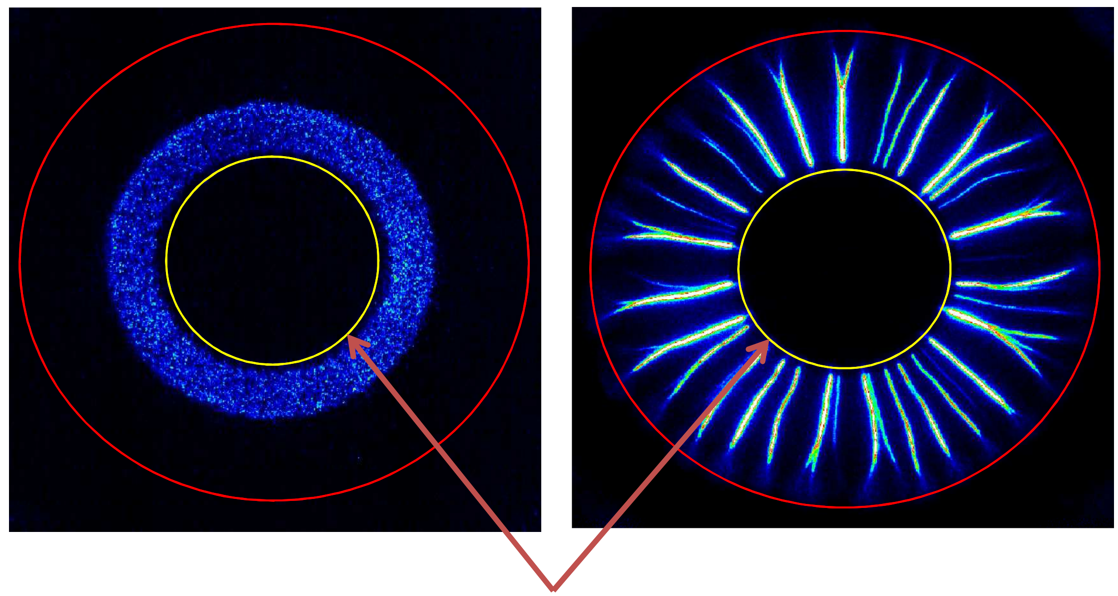


D=2 cm HV electrode

Cylindrical electrode configuration

Outer diameter 50 mm;
HV electrode diameter 20 mm

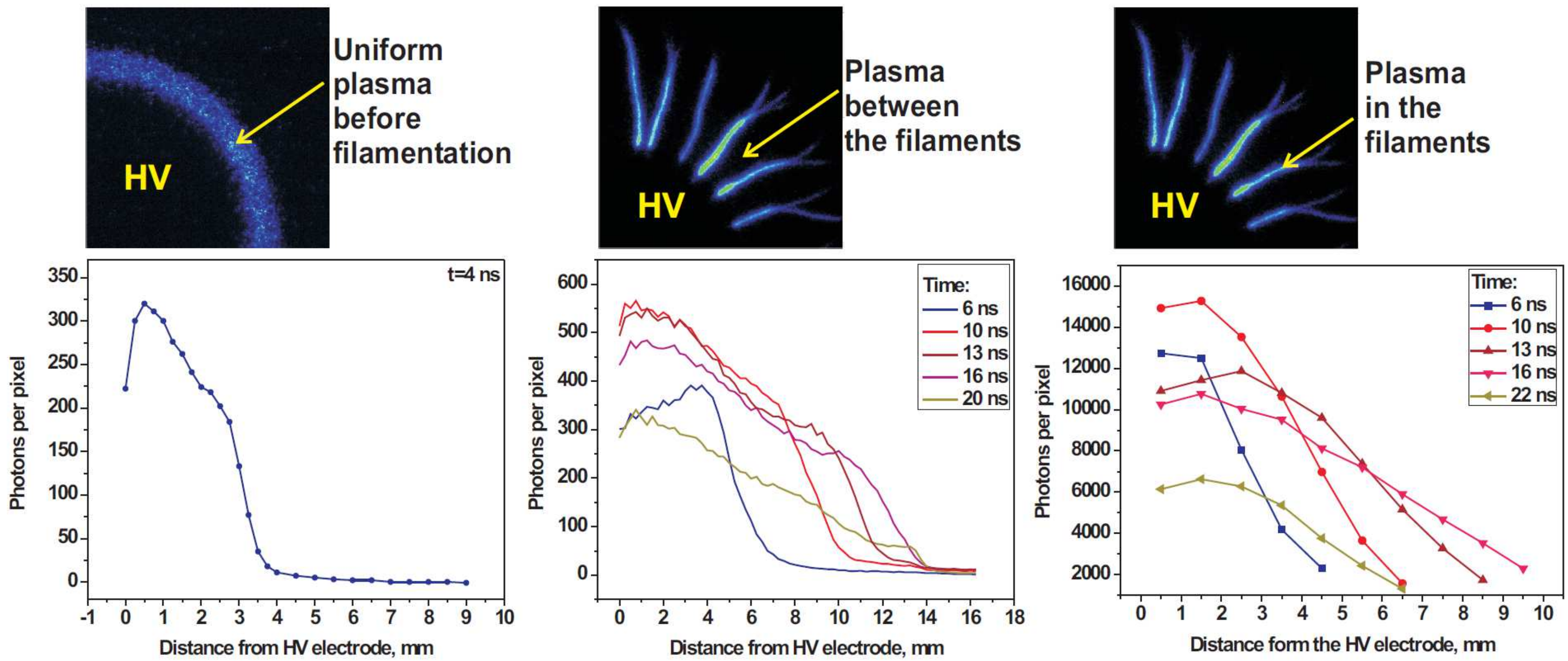
Filamentary mode, V=-46 kV, 4 bar, Air



HV electrode

Camera gate is 0.5 ns

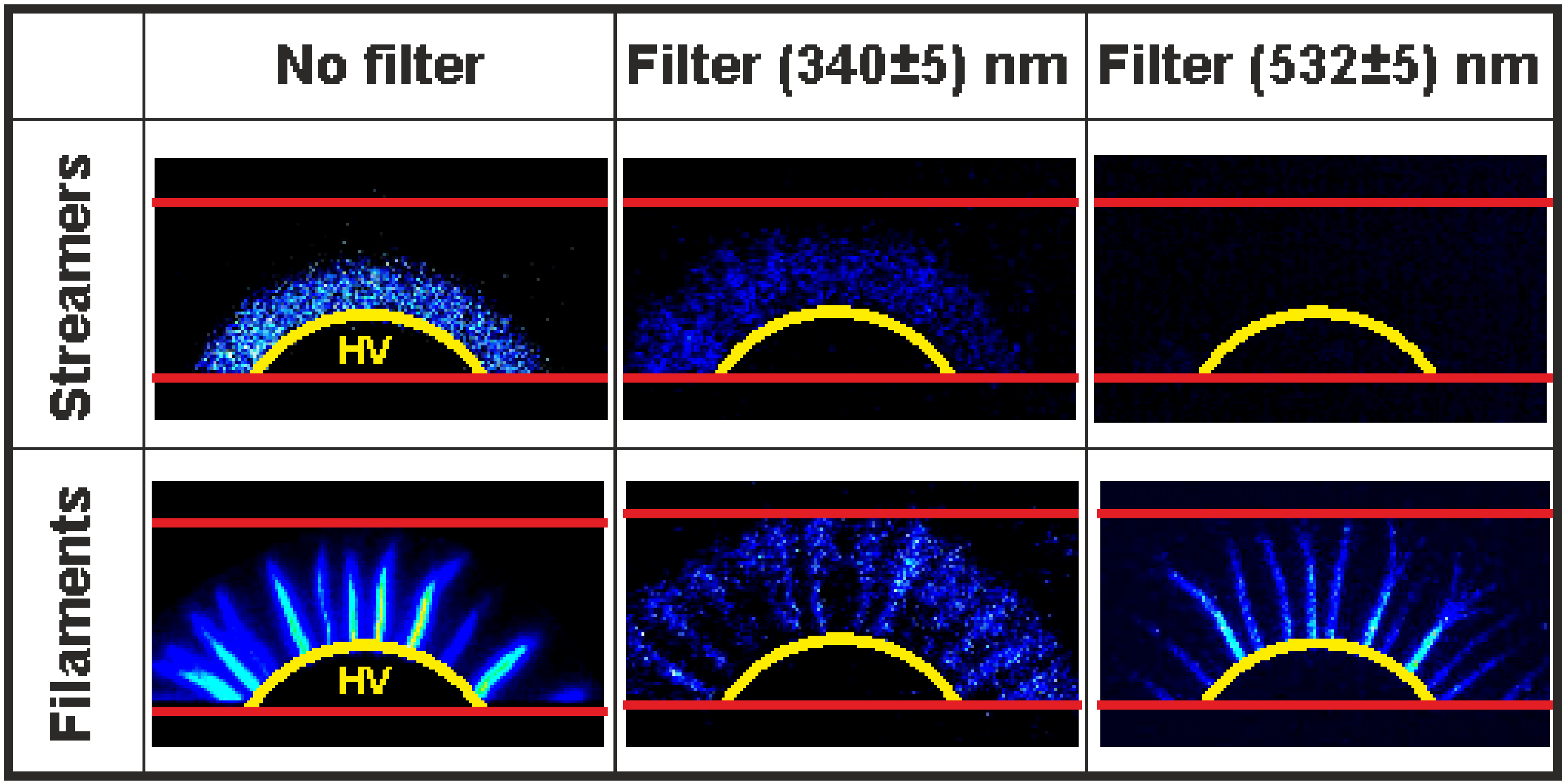
Analysis of emission intensity
(Streamer vs filamentary mode)



$$I_{11ns}^{fil}/I_{11ns}^{dif}/I_{4ns}^{dif} \sim 50/1.5/1$$

Radial distribution of the frontal discharge emission; *P=4 bar, U=-47 kV.*

Spatial distribution of emission



How to get the filament spectra

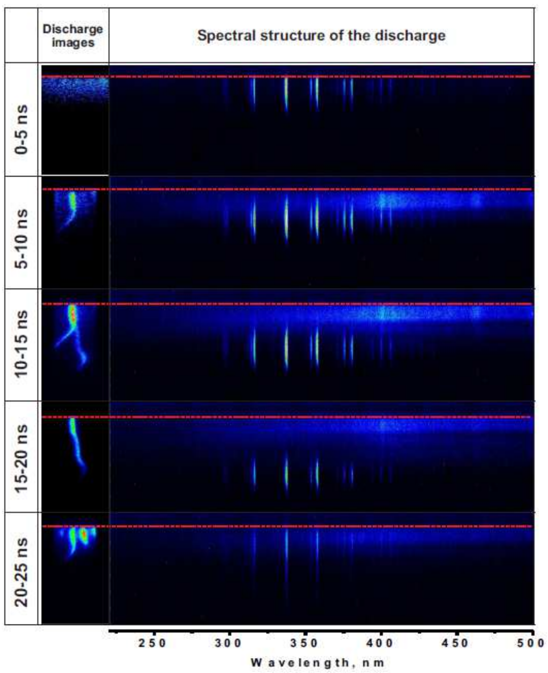
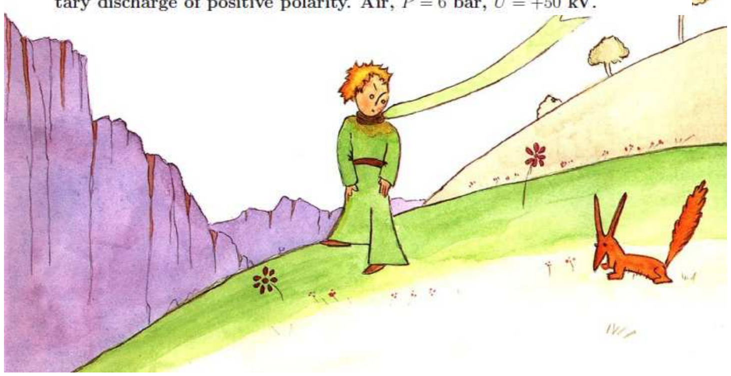
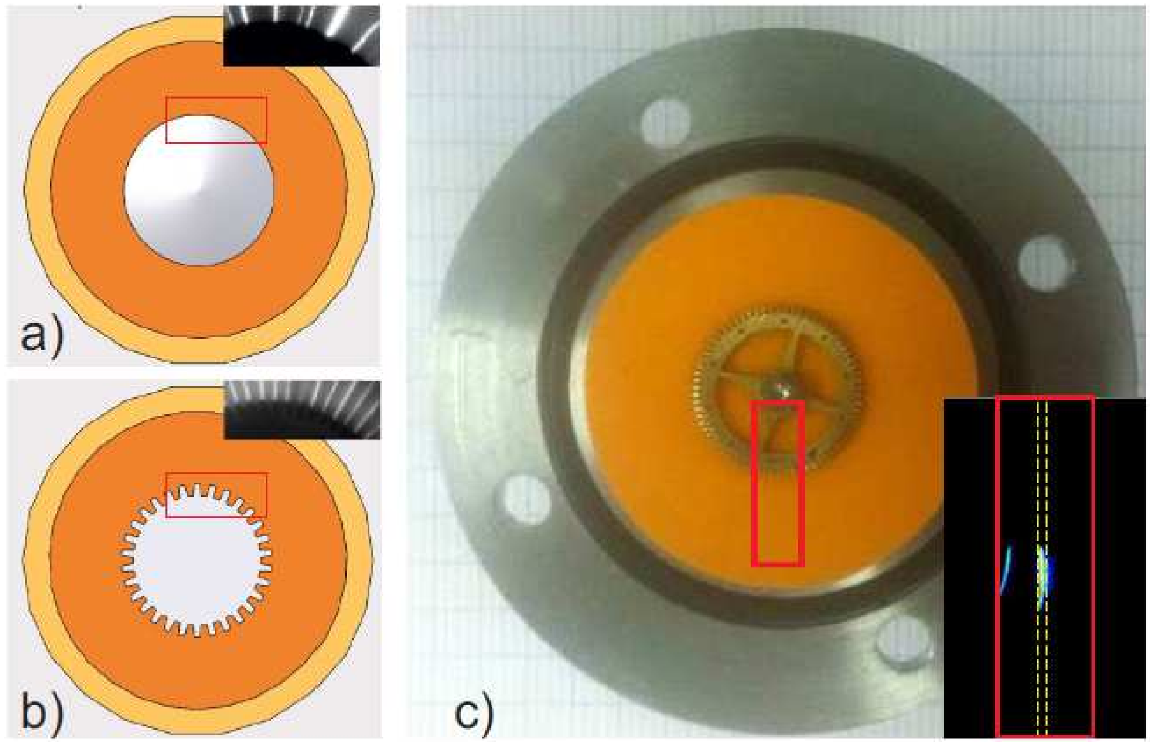


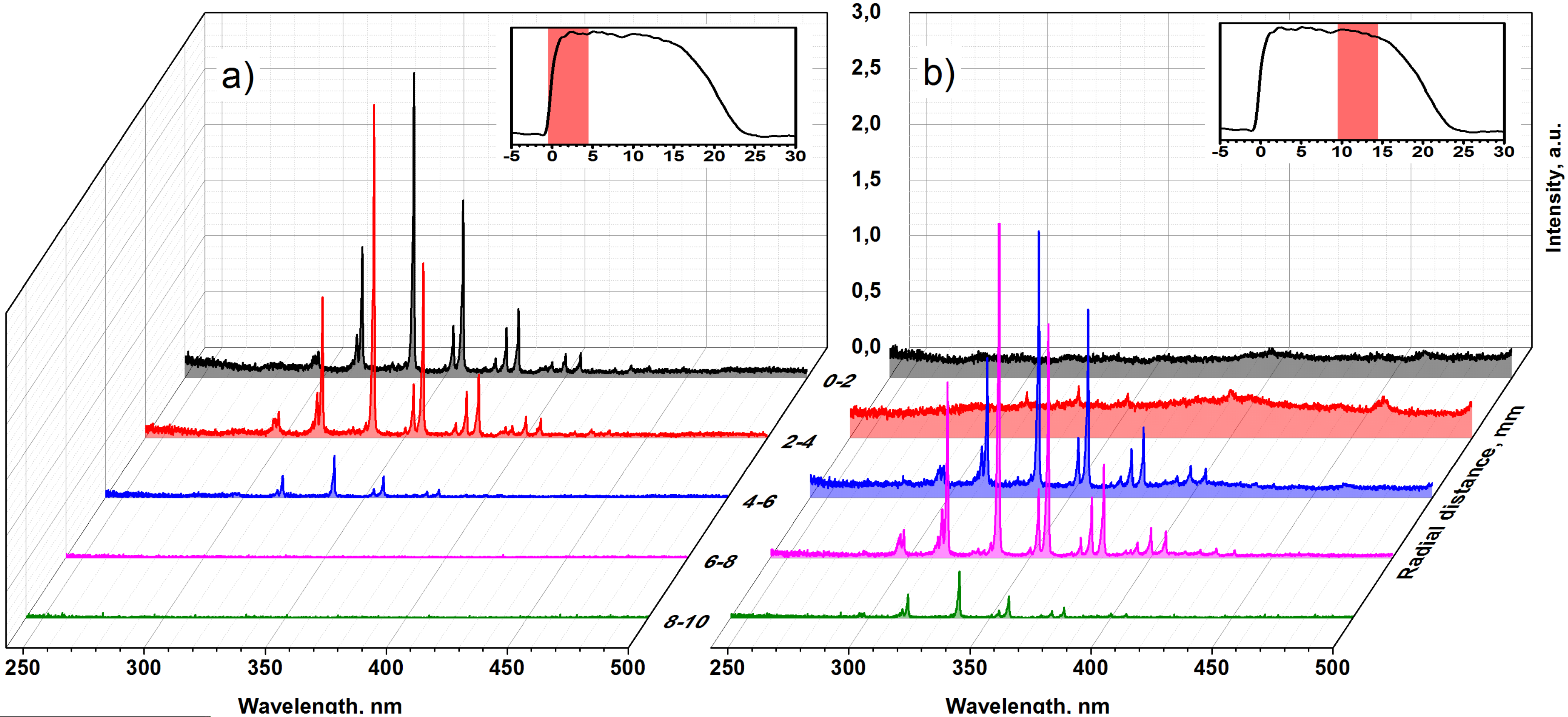
Figure 5.22: ICCD images and time-resolved 2D spectra of the filamentary discharge of positive polarity. Air, $P = 6$ bar, $U = +50$ kV.

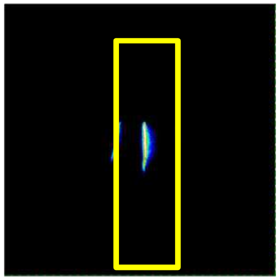




Single filament is aligned with the entrance slit of the spectrometer

Continuous spectra in filamentary discharge

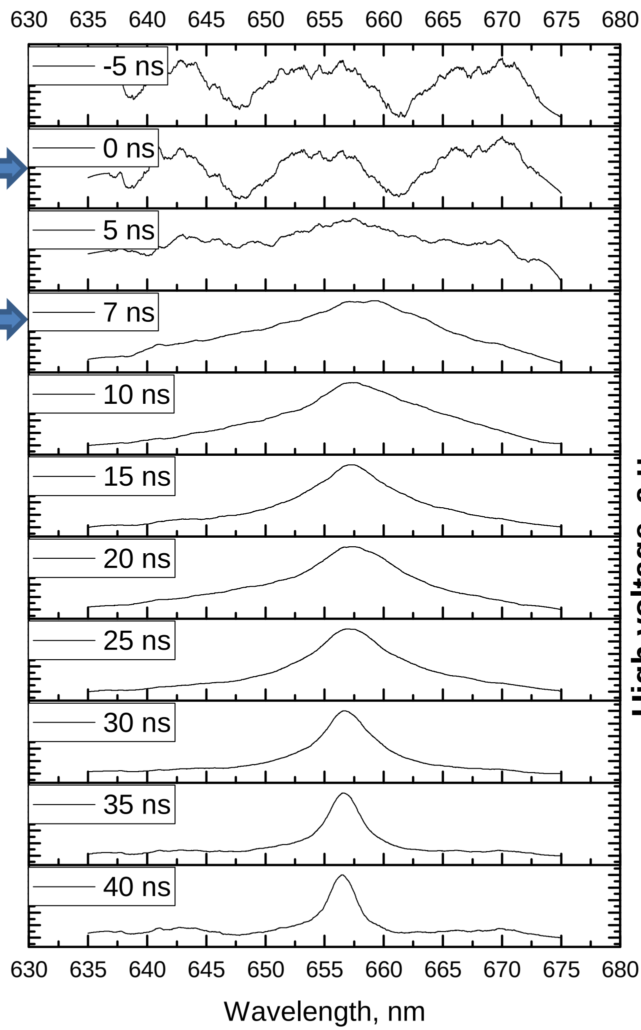




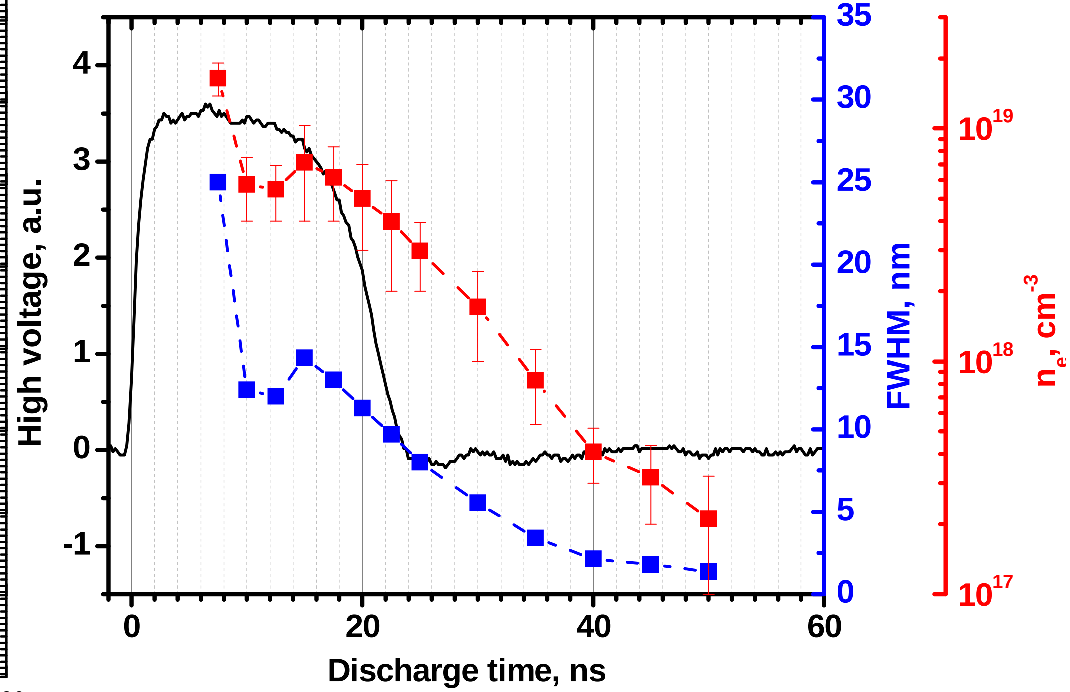
Broadening of H_α line

Discharge starts

Filaments start



Filamentary discharge in N_2:H_2 (7:1) mixture P=8 bar. Electron density measurements with H_α line (656 nm) broadening. Camera gate 5 ns

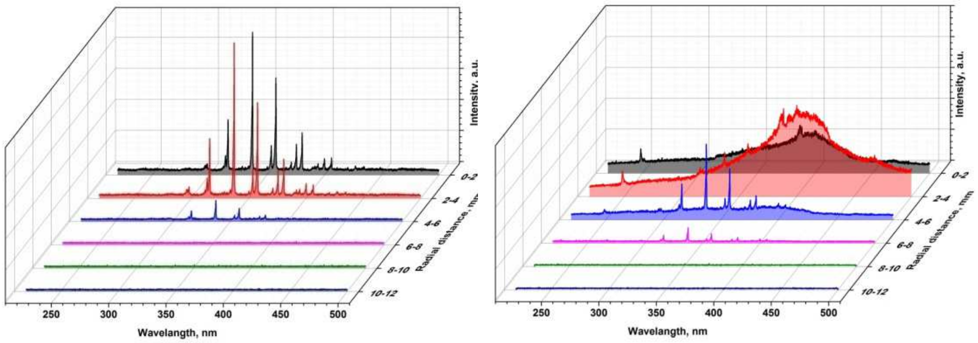


Recombination emission in the filament

Electron density from recombination emission

SPS (337.1 nm) is a reference radiation

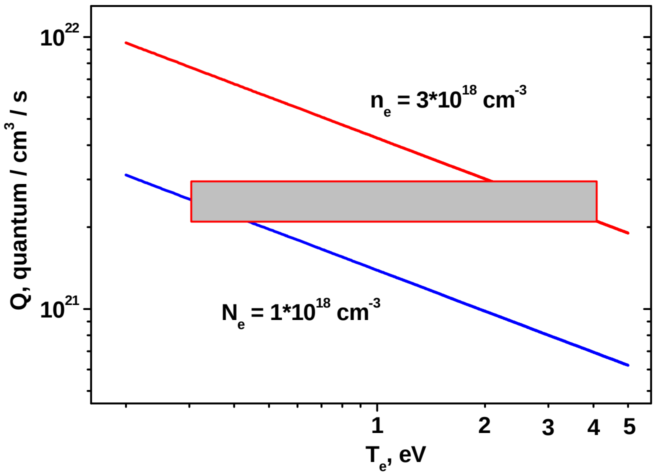
$$\begin{cases} N_2(C)=k_C(E/N)\cdot n_e\cdot N_2/\,v_q \\ Q_C=N_2(C)\cdot F_{FK}\cdot A_{00} \\ Q_C=3\cdot 10^{21}\,\text{quantum/cm}^3\text{/s.} \end{cases}$$



$Q_C(t=0\ ns)/Q_{CW}(t=5\ ns)\sim(1.5\text{-}2)$

$$Q_{CW}(\omega)=C_0\cdot\frac{n_e\cdot n_{ion}}{\sqrt{T_e}\cdot\eta\omega}d\omega=(1.5-2)\cdot 10^{21}\,\text{quantum/cm}^3\text{/s}$$

At λ = 337 nm and $\Delta\lambda$ = 3 nm, $d\omega = 5\cdot 10^{13}$ s^{-1}



In the discharge T_e~2-4 eV → $n_e\sim 3\cdot 10^{18}$ cm^{-3}
In the afterglow T_e~0.5 eV → $n_e\sim 10^{18}$ cm^{-3}

Conclusions

Nanosecond dielectric barrier discharge (nSDBD) provides ignition of different fuels in a wide range of stoichiometries

At high gas densities, nSDBD simultaneously provides hundreds of ignition sites distributed in space. The geometry of the ignition and following combustion can be adapted to provide the highest possible efficiency of the system

Physics of filamentation in high pressure nSDBD is under study now ($n_e=10^{19}$ cm^{-3} is achieves during a few nanoseconds in a single-shot mode)